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THE SPOKANE FLOOD BEYOND THE CHANNELED SCABLANDS

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ABSTRACT

The channeled scablands of the Columbia Plateau in Washington are extensive elongate denuded tracts of basalt, deeply scored by huge high-gradient glacier-born rivers. As physiographic features they are unique. All the rivers which produced them converged to Snake and Columbia valleys, and the record of the tremendous flood thus engendered has been found all the way from the plateau scablands to Portland. Columbia River Valley below the confluence of Snake River carried a flood which at Wallula Gateway was 2 miles wide and reached 750 feet above present river level, at Arlington was 7 miles wide and 450 feet above present river level, at Lyle was 3 miles wide and 430 feet above present river level, and at Portland was nearly 20 miles wide and 350 feet above present river level.

The field evidence for the flood consists of (1) noteworthy, even spectacular, denudation and erosion of slopes below the upper surface of the flood, (2) spreading of the river in favorable places back among preglacial hills, (3) deposition of great gravel bars, some of them nearly as thick as the flood was deep, (4) damming of Snake River above the entrance of the glacial rivers by a delta built upstream against the course of the Snake, and (5) deposition of the Portland Delta, 350 feet thick, 200 square miles in area, and with bars 100 feet high on its surface.

THE PHYSIOGRAPHIC SETTING FOR THE FLOOD

Channeled scabland is limited to that part of the Columbia Plateau which lies between, and above the confluence of, the Snake and Columbia River canyons (Fig. 1). The slope of the plateau in general is southwestward, away from Columbia River on the north and toward Snake River and the lower part of the bounding Columbia

on the south and southwest. Almost all the drainage of the plateau is consequent on this slope.

The Spokane ice sheet crossed the Columbia Valley north of the plateau and advanced a few miles out on it along almost the entire northern margin. Water from the melting of this ice flowed in the preglacial consequent drainage system, entering at or near the heads of these valleys and traversing their entire lengths. The ablation of the Spokane ice sheet must have been extraordinarily rapid, for the volume of water was very great, almost incredibly great, and in spite of high gradients to draw it off, the pre-existing valleys first entered were inadequate to carry it all, and the flood spread widely in a complicated group of anastomosing routes. This pattern is unique in that all the routes were greatly eroded, many of them being developed into canyons of notable proportions by the glacial streams, and some of them crossing prominent preglacial divides on the plateau.[1]

The pre-Spokane drainage of the plateau which entered the Snake was conveyed to one main route, that of Esquatzel Coulee, near Pasco. During the Spokane epoch, two other discharge ways were formed, one through Devils Canyon, near Kahlotus, and one through Palouse Canyon, between Hooper and Perry. The Palouse Canyon route now carries most of Snake River's share of the plateau run-off, Devils Canyon carries none, and Esquatzel Coulee carries but a small portion. This change from preglacial conditions was due to the profound erosion by glacial waters in Palouse Canyon. Greater volume and higher gradient at this place determined the change.

Columbia River had two considerable pre-Spokane tributaries from the plateau, Moses Coulee and Crab Creek. These proved inadequate to carry the Spokane flood, and six others were opened: "The Potholes," Frenchman Springs, and the Koontz Coulee group of channels, the first two being simply cataracts over the cliffs of Columbia Valley. All of these discharge ways leave the west side of that part of the plateau concerned in this study. None of them now carry plateau drainage.

[1] Set forth in some detail in the writer's paper on "The Channeled Scablands of the Columbia Plateau," *Jour. Geol.*, Vol. XXXI (1923), pp. 617–49.

FIG. 1.—Sketch map of the region affected by the Spokane flood

The history of the channeled scablands, very briefly outlined above, has been accepted only with considerable reservation and qualification by many, for the volume of the flood described and the results it produced surpass anything previously known in river phenomena. That this huge volume was a verity, the character of Snake and Columbia valleys below the entrance of the Spokane rivers amply proves. This paper describes the remarkable features produced in these valleys by the concentration of discharge from the scabland rivers. Though details generally render a paper less readable, they are presented here to show more clearly the nature of the field evidence.

THE CHANNELED SCABLANDS

The phenomena which characterize the channeled scabland of the Columbia Plateau are briefly summarized here. The argument thus may be clear without a reading, or re-reading, of the writer's previous papers on the subject.[1]

1. Channeled scabland (Fig. 2) is the eroded surface of the Columbia basalt formation. It is bare rock or is but thinly covered with basaltic débris. It is distributed in an intricate interlacing pattern whose strands are traceable up-gradient to, but not across, the area glaciated by the Spokane ice sheet, and down-gradient to, but not across, the Snake and Columbia valleys. This bare, or nearly bare, rock has a total area of about 2,000 square miles, and its linear tracts are bounded by thousands of miles of cliffs. Basins excavated in the solid basalt are common, many of them at the foot of cliffs transverse to the linear tracts, the sites of former cataracts. Knobs of basalt standing on the floor of the channels are common also.

2. Stream gravel, 99 per cent basalt, occurs in all scabland tracts. Except rarely, it does not occur in terraces, nor does it cover the floors of the channels. It is deposited in great rounded mounds, commonly on the lee side of basalt knobs and elongated with the channels. Less commonly, it lies high up on the sides of the scabland

[1] "Glacial Drainage on the Columbia Plateau," *Bull. Geol. Soc. Am.*, Vol. XXXIV (1923), pp. 573–608; "The Channeled Scablands of the Columbia Plateau," *Jour. Geol.*, Vol. XXXI (1923), pp. 617–49; "The Dalles Type of River Channel," *Jour. Geol.*, Vol. XXXII (1924), pp. 139–49; "The Age of the Spokane Glaciation," *Amer. Jour. Sci.*, Vol. VIII (1924), pp. 336–42.

channels against the cliffs, though here it generally has the rounded, elongated forms. These gravel deposits are interpreted as bars made by the glacial rivers.

3. Above the level of the scablands and their associated gravel deposits is a deep mantle of loess on the plateau. This loess deposit has been dissected to maturity and almost everywhere is in gentle slopes. But along the linear scabland tracts, the loess is steeply scarped, the slopes averaging 30°, all facing and descending to the scabland. There are many isolated hills of loess entirely surrounded

FIG. 2.—Channeled scabland on the Columbia Plateau. The figure in the picture stands on the brink of an abandoned cataract. Photo by F. L. Pickett.

by scabland (Fig. 3), and these commonly have striking prows which point up the scabland gradient. Some of these isolated loess hills, bounded by steep slopes, have the rounded, elongated deposits of gravel on the down-gradient end. The scarps are interpreted as river bluffs of the Spokane glacial streams, produced when the preglacial valleys were not sufficiently deep in basalt to contain the flood which was poured into them. The anastomosing pattern of the whole group of associated phenomena is likewise the consequence of a greater volume than some valleys could carry away, the waters flooding over many minor and some major divides of the plateau.

THE SPOKANE FLOOD IN SNAKE RIVER VALLEY

Between Lewiston and Riparia.—At Lewiston, Idaho, Snake River occupies a structural valley in whose northern wall the Columbia basalt flows are tilted 60° from horizontal. It leaves this open valley a few miles below the Idaho-Washington boundary line and traverses a narrow, winding canyon, cut in nearly horizontal flows of basalt, thence nearly to its junction with Columbia River.

The distance from Lewiston to Riparia is about 100 miles, and the descent is 200 feet. Terraces of river gravel occur on the inside of almost every curve in the course. None of these are more than

FIG. 3.—Isolated loessial hills on the scabland of the plateau. Photo by F. L. Pickett.

50 feet above the river, if talus and alluvial fan deposits on top of them are not reckoned. Less than 50 per cent of the gravel of which they are composed has been derived from the Columbia basalt. Though the canyon walls are steep, there are no great cliffs, and a mantle of débris and vegetation occurs on most of the slopes. All of these are normal features, and none suggests the occurrence of the Spokane flood in this part of Snake River Valley.

Between Riparia and the mouth of Palouse River.—A great terrace of gravel, 150 to 260 feet above low-water level, lies on the north side of Snake River Canyon in this stretch. Much of it is flat-topped. Exposures are numerous along its steep scarp. Almost without ex-

ception the gravel is foreset-bedded, and almost without exception this foreset bedding dips *up* the Snake River Valley. The amount of gravel not derived from the Columbia basalt in most sections does not exceed 1 per cent. The pebbles are worn, well sorted, and progressively smaller with increasing distance *up* the Snake. At the upstream terminus of the great terrace, a mile west of Riparia (Fig. 4), all the material is fine enough for highway gravel. The summit here is about 150 feet above the Snake. Though the Snake descends westward, the terrace top descends eastward.

FIG. 4.—Upstream terminus of the Riparia terrace. Foreset beds dip to the right, or up the Snake, parallel with the terminal slope.

There is a terrace on the south side of the Snake comparable to the one described except that its extent along the canyon is much less. Another gravel deposit on the south side, also opposite the great terrace, lies in the mouth of the tributary valley of Tucannon River. Its surface is lower than that of the great terrace and descends southward *up* the Tucannon Valley to Starbuck, a distance of 4 miles. Here it meets the bottom of the pre-Spokane Tucannon Valley, descending toward the Snake. The stratification of the basaltic gravel of this deposit is inclined, and the dip is *up* the tributary. The material is progressively finer, also, as the distance from the Snake is greater. Some of the gravel apparently was carried into the lower part of Tucannon Valley from the east, across the angle

between the Tucannon and the Snake, but most of it came up the Tucannon.[1]

These three remnants of a great gravel deposit in Snake River Valley indicate

1) a supply of river gravel introduced some miles below Riparia and Starbuck, and carried eastward up the Snake and Tucannon valleys,

2) a depth of ponded water at Riparia of about 250 feet, and

3) the basalt plateau as the source of the gravel.

This deposit was made rapidly, else Snake River would have filled its valley above Riparia with the coarse débris of its hundreds of mountain-born, high-gradient tributaries. There is no evidence of such deposits for at least 100 miles above Riparia. The ponded Snake, if 250 feet deep at Riparia, was 50 feet deep at Lewiston.

Nothing on the south side of Snake River even suggests that the gravel of these terraces came from that portion of the plateau. On the contrary, the features of Tucannon Valley below Starbuck indicate that the débris came from the northern side, which bears the scablands.

Between Palouse River and Devils Canyon.—There are many large gravel deposits in this stretch, all falling into two groups: great rounded mounds, and flat-topped terraces. The great mounds are strictly only half-mounds, for they rest against the canyon walls somewhat like alluvial fans. Almost all of them occur on the inside of the broad curves of the canyon's course. Almost all of them slope from their summit contact, at the base of a basalt cliff, down toward the middle of the valley. These slopes are all convex. Where there is no notable cliff back of the mound, the gravel deposit has a convex top and is highest a little out in the valley. One such deposit lies like a great dam across the mouth of a tributary valley, and a narrow gash has been cut by that tributary subsequently. These half-mounds stand 150 to 200 feet above the river-level, and in the scarps cut by the Snake the gravel descends to river-level. In com-

[1] I. C. Russell (U.S. Geol. Survey, *Water Supply Paper* No. 4. p. 21) noted this gravel deposit in the Tucannon valley below Starbuck and interpreted it as Snake River gravel carried back up the tributary valley. He noted also great gravel deposits in the Snake Canyon. His interpretation is couched in the conventional terms of overloading of the main stream by excess supply from the headwaters.

position, they are 99 per cent Columbia basalt. Their structure is largely foreset, with the dip consistently *down* the canyon. They bear almost no gullies, ravines, or other erosional slopes except the steep riverward faces. Some of the mounds show a horizontal fluting and a minor mounding on their slopes which can only be original, depositional outlines, as, indeed, the convex slopes are original slopes.

The deposits of this group are bars. They were deposited during one short episode when the stream was deeper than they are high, yet had a mid-current velocity sufficient to keep most of the channel open from side to side and from top to bottom. The flood in which they were built came from the surface of the plateau, carried almost nothing but basaltic débris, and entered the Snake Canyon somewhere above the stretch in which they occur. This flood subsided so quickly that there was almost no modification of their outlines by either erosion or deposition from the lowering stream. Hillside and roadside gullies often show similar phenomena in miniature after torrential rains.

Only two flat-topped terraces were seen in this part of Snake Canyon. One is on the south side, opposite the mouth of Devils Canyon, the other is at Davin Station, on the north side, a few miles below the mouth of Palouse River. The summits of both are well above the tops of the mounded bars, the one on the south side 350 feet above the Snake, the one at Davin 200 to 250 feet above. Both are composed of basaltic gravel from top to bottom and scarcely touched by gullies.

In brief, then, the features of Snake River Valley for a few miles both up and down stream from the mouth of Palouse River indicate the entrance at that place of a great river from the north, far surpassing the proportions of either the Palouse or the Snake of today. The volume of this river actually ponded the Snake for 100 miles or so upstream, and into this pond was built a deltaic gravel deposit, reaching to Starbuck in the tributary Tucannon and nearly to Riparia in the main valley. And it is here, at the mouth of Palouse River, that the greatest contribution from the Spokane flood across the plateau scabland entered Snake River. The evidence for this has been presented in a previous paper and will not be reviewed

here. The glacial river at its inception was 10 or 15 miles wide, and in its central portion it eroded at least 500 feet deep just above its junction with the Snake. The Davin terrace lies at the debouchure of a distributary course of this river, and the plateau scabland extends almost to the brink of the Snake Canyon here. In a similar fashion the great terrace below Riparia can be traced northward to the scabland along the eastern margin of the wide glacial river.

Mouth of Devils Canyon.—Devils Canyon was eroded by overflow from Washtucna Coulee across a preglacial divide to Snake River Canyon during the Spokane epoch. As shown by the scarped loessial hills margining this glacial river course, the flood rose to 1,300 feet A.T. in Washtucna Coulee, at which altitude part of it spilled over to the deeper valley, and the large torrential stream thus formed rapidly eroded Devils Canyon. Before the close of the episode, the canyon was gashed 500 feet deep in basalt, all but cutting the divide down to the floor of Washtucna Coulee. The spill-over apparently entered a short preglacial tributary of Snake River, for the mouth of Devils Canyon is flaring, unlike the extreme narrowness of the rest of it. In the middle of this flaring mouth is a basalt knob, of no remarkable proportions, but characteristically a scabland knob, and flanked by post-Spokane talus. It is clearly an erosional remnant of the pre-Spokane floor of the tributary. Below this knob, and projecting in part out into the Snake Valley beyond the line of the canyon walls, is a gravel deposit about 160 feet above the level of Snake River. The surface of this deposit bears an exceptional ridge, shaped in ground plan like a horseshoe, with the concavity facing up Devils Canyon and the two ends abutting against the walls of the flaring mouth. The middle of this semicircular ridge is about 60 feet above the rest of the gravel deposit. It is symmetrically lower on both limbs, the lowest places being next to the rock walls. The slopes of the ridge are gentler toward the concavity, i.e., upstream, than they are toward Snake River. Post-Spokane run-off has cut a narrow ravine through the ridge at its contact with the eastern rock wall,[1] but when the glacial river ceased to flow,

[1] The topographer who sketched this ridge was quite at sea as to its origin. The Connell sheet shows it as a minor ridge projecting from the west wall of Devils Canyon and due to stream erosion.

this semicircular ridge was complete and inclosed a basin in the mouth of Devils Canyon. In this basin stood the eroded basalt knob above noted.

Closer scrutiny of the ridge shows that it is fluted radially, or composed of low radially elongated mounds, largely coalesced, and that on its downstream face, out in Snake River Valley, are traces of larger, older flutings on which the semicircular ridge has been built.

This curious gravel ridge is a bar. It is identical with the bars formed across torrential streams where there is a slackening of velocity because of increased width of channel and decreased gradient. It is duplicated in roadside gutters after heavy rains. It is evidence conclusive that a great torrent made Devils Canyon, that that torrent abruptly ceased to flow, and that the surface of Snake River at that time was more than 220 feet above its present summer level. The fact that the gravel deposit extends down almost to the river-level shows that Snake Canyon was then eroded approximately to present depth and the stream at that time was more than 220 feet deep.

The materials of the gravel deposit are not well shown. In the exposures available, the gravel is poorly sorted and little worn. It is practically all basalt. The large amount of interstitial silt in the gravel suggests its derivation from the destruction of loessial hills on the scablands farther north.

Snake River Junction.—In many ways the vicinity of Snake River Junction[1] exhibits the remarkable changes caused by the Spokane flood better than any other place in the canyon. An observer standing on the hilltop centrally located in Section 11, T. 10 N., R. 33 E. (Fig. 5), $2\frac{1}{2}$ miles southeast of the junction, can see for miles both up and down the valley. The canyon proper, with very steep, rugged, bare cliffs and ledges, lies below a broad higher valley floor that is several times as wide as the top of the canyon. Above this broad floor rise the gently rolling loessial hills of the plateau, but almost without exception their slopes toward the broad floor are about 30°.

[1] Junction of Spokane, Portland and Seattle Railroad and Lewiston branch of Northern Pacific Railroad.

The severely eroded bare basalt below the higher broad floor, typical scabland in its character, carries great isolated gravel deposits with rounded summits and convex slopes. The higher floor is 1,000 feet A.T. in maximum elevation at Snake River Junction, where it is determined by the upper surface of the Columbia basalt formation, from which the loess has been removed by the wide

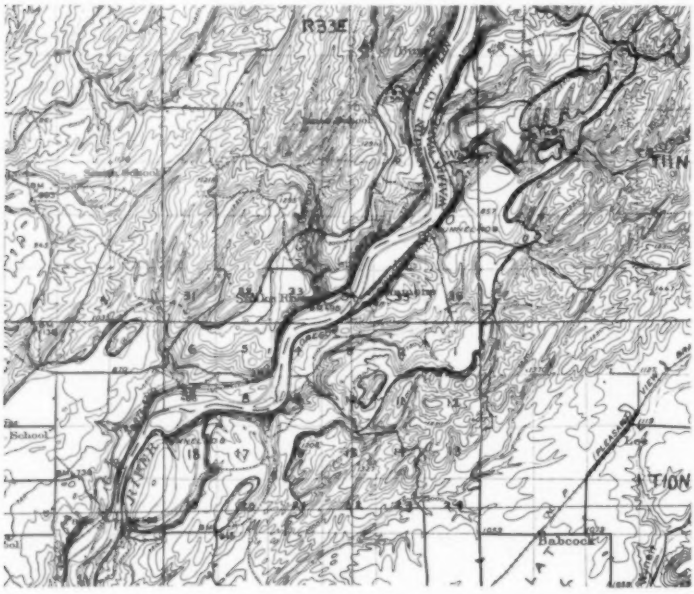

FIG. 5.—Vicinity of Snake River Junction, showing the loess-covered plateau, the extent of the upper floor of scabland basalt from which the loess has been removed, its steep margining slopes of loess, isolated hills of loess, and the abandoned portions of Snake River Canyon. From the Wallula, Washington, topographic map, U.S. Geological Survey.

glacial river, and on which gravel has been spread. The absence of such a floor from Riparia down to the vicinity of Snake River Junction is due to the failure of the flood to reach the upper limit of the basalt cliffs.

In the extreme northwest corner of Section 11, above noted, is an isolated loess hill, with slopes of 30°, with elongation parallel to

the Snake Canyon and with a prow pointing up the canyon (Fig. 6). Between it and the hill, centrally located in this section, is a flat-bottomed valley, walled by loess bluffs and floored by Columbia basalt at about 1,025 feet A.T. Here a small part of the glacial flood spread across a minor divide of the invaded loessial drainage system, to re-enter the main flood about a mile farther down. This isolated hill is typical of hundreds in the plateau scabland.

But at the cornering of sections 1, 2, 11, and 12 is another small preglacial valley in loess, similarly oriented and proportioned and with similar altitude of floor, but with the divide at the head intact. The divide is composed of loess and lies a little above 1,100. We

FIG. 6.—Isolated hill of loess, 2¾ miles southeast of Snake River Junction

conclude, therefore, that the glacial flood which swept the loess from Section 1 and made the steep cliff in loess along its southern margin failed to rise to 1,100 feet A.T.

East of Simmons Station is a greatly eroded hill of nearly bare basalt (Sec. 35, T. 11 N., R. 33 E.), its summit a little below 1,100, with Snake River on the northwest side and a valley in basalt on the east fully as broad as the Snake Canyon but 250 feet less in depth. On the downstream end of the hill is a bar of basaltic gravel 250 feet thick. The broad streamless valley east of the hill is a part of the pre-Spokane course of Snake River, the stream having located and eroded a more direct route during the flood which so greatly denuded the basalt hill. This abandoned portion contains remnants

of a stained and indurated river gravel, of which not more than 25 per cent was derived from the underlying formation.

A great bar along the Spokane, Portland and Seattle Railroad, 2½ miles northeast of Snake River Junction, is 400 feet thick. The gravel pit excavated by the railroad here has a scarp 200 feet high. The gravel is unindurated and slides easily, so that the structure is difficult to decipher. But it is 99 per cent basalt.

One more feature in the vicinity of Snake River Junction may be described and the list then closed, though every mile of the canyon here contributes to the history of the Spokane flood. The locality is between Page Station of the Spokane, Portland and Seattle Railroad and Tunnel No. 8 on the Oregon-Washington Railroad, and involves 4 square miles, most of it east of the river. The canyon here is narrower than at any other place in the plateau. East of the narrow place is a basalt hill 400 feet above river-level, possessing the typical severely scrubbed scabland aspect. The hill is separated from the rest of the higher land to the east by an abandoned valley which is open to the Snake at Tunnel No. 8 and opposite Page. Its floor is nearly 150 feet above the present river. Depending from the downstream end of the bare rock hill and overlying it in part is a gravel bar about 200 feet thick, whose convex outlines are unmistakable. The growth of the bar has constricted the southern part of the abandoned valley. The present course of the Snake through the exceptionally narrow canyon west of the hill departs from the fairly symmetrical meandering pattern it elsewhere possesses in the vicinity of Snake River Junction. Were the narrow canyon filled, the bar removed, and the Snake replaced in the old course east of the scabland hill, the symmetry would be restored, all steeper bluffs would stand on the outside of curves with the river undercutting them. and a uniform width of valley would exist throughout. It seems probable that the Spokane flood, which at its inception was at least 250 feet deep over the top of this hill, cut across a pre-Spokane spur in the valley's course and eroded the narrow canyon west of the hill. If this be correct, then Snake River Canyon was deepened here about 150 feet by the glacial stream.

In summary, the vicinity of Snake River Junction records a river of dimensions so great that the pre-Spokane valley was but a

channel for it. The glacial waters, in prodigious volume, reached at least 1,000 feet A.T., though the surface of the river today is but 400 feet A.T. here. About 150 feet of deepening in basalt occurred, all exposed rock slopes were greatly eroded to typical scabland forms, two new routes were cut across the pre-existing curves, huge amounts of basaltic gravel were eroded and transported. All the features of the plateau scabland are here. Bluffs of loess 250 feet high and with 30° slopes face the broad scabland floor, isolated prow-pointed hills of loess stand on the margins of the broad floor, bars of basaltic gravel with the typical convex slopes so often seen in the plateau scablands lie in protected places below the level of the broad floor, and cliffs without streams at their bases have talus standing three-fourths of the height of the original cliffs. The glacial river was at least 400 feet deep and 3 miles wide here at its inception.

THE SPOKANE FLOOD IN COLUMBIA VALLEY ABOVE THE MOUTH OF SNAKE RIVER

Columbia Valley between the limits reached by the Spokane ice sheet and the mouth of Snake River has not been studied as carefully as it deserves. But enough is known to warrant the statement that nothing comparable to the Spokane features of Snake River Canyon is found in it. No great bars are known, no bluffs of loess, no relocations of the stream course, almost no scablands. Yet the flood was there and left its record.

Columbia Valley is deeper and considerably wider than Snake Canyon, and carried its share of the Spokane flood without rising to the summit of the basalt cliffs. Hence the absence of the steepened slopes in loess and of scabland above and margining the river valley. Much of the water entering it passed through settling-basins which trapped the waste of the scablands. Much came directly from the margin of the ice sheet. The basaltic gravel which did enter appears to have been mingled with older gravel, and the striking dominance of basalt, seen in Snake River bars, is absent here. Evidence of the height reached by the flood has been found largely in the features of the scabland spillways from the plateau.

Moses Coulee.—The largest single spillway was Moses Coulee, a pre-Spokane drainage way which was greatly modified during the

Spokane epoch. In Columbia Valley at its mouth, and extending back up the coulee, is a gravel deposit more than 300 feet thick, the highest part of which is 925 feet A.T. and the lowest surface about 800. Since the coulee carried some discharge from the Wisconsin ice sheet, subsequent to the Spokane glaciation, this lower surface, which floors most of the mouth of the coulee, may not date from the earlier epoch. But the higher part certainly does. And below the mouth of Moses Coulee the high gravel terrace lies against the foot of an exceptionally high steep cliff of basalt. The cliff strikingly truncates a number of short tributaries to the Columbia and their separating spurs. It constitutes the east side of Columbia Valley and of Moses Coulee, and thus is traceable into the scablands. Only a great stream undercutting at about 1,000 feet A.T. could make this cliff, and the character of its talus dates it as Spokane in age.

"*The Potholes.*"—Ten miles south of the mouth of Moses Coulee is "The Potholes," a huge alcove caused by retreat of a scabland cataract. Not considering the remarkable holes, which are more than 125 feet deep in bedrock, the cataract made a sheer leap of 200 feet from the brink of the Columbia cliffs to the surface of a prominent rock terrace of the Columbia Valley, itself about 400 feet above the river. Over the edge of this terrace the stream spread in several channels and leaped again, this time about 125 feet. Much less work was done by the cataract on the edge of the terrace than on the summit of the cliffs, and for this notable difference a reason must be found. The terrace extends northward from "The Potholes" along Columbia Valley for several miles, rising upstream about 80 feet to the mile with the gentle tilt of the basalt flow which holds it up. For 2 miles north of the ancient cataract, the surface of the terrace is greatly channeled in typical scabland fashion, with "holes" and rock islands in complex profusion.[1] East of this scabland on the terrace top is the upper cliff with three-fourths talus.

Farther north, however, the terrace surface bears no scabland, and the cliff has soil-covered talus to the very summit. The Spokane flood, therefore, entered on this southward-sloping rock terrace at an

[1] Some of these are shown on the Quincy sheet, but most of them are too small to be caught by any contour.

altitude of about 1,200 feet A.T., scored its surface, and undercut the cliff above it. The three-fourths talus of this cliff indicates that all the wastage has accumulated since the scablands were formed. But 1,200 is the altitude of the brink of the upper Potholes cataract. No cataract existed, then, at the beginning of the spill-over. Its development waited until the main Columbia Valley flood subsided, though the scabland flood was still running at full volume. The explanation for this seems to be that some constriction farther down the Columbia Valley held up the great flood at first, but was rapidly eroded during the episode. The surface of the stream therefore fell until, late in the cataract's history, the rock terrace was exposed and the lower falls took origin. Such a constriction exists, and is described in this paper.

Gable Butte and Gable Mountain.—Near the towns of Hanford and White Bluffs, 35 miles above the junction of Snake and Columbia rivers, the Columbia Valley is 15 miles wide. Most of the valley floor here lies about 500 feet A.T., though the river surface is below 375. This 500-foot floor consists of a great gravel deposit which extends southward to and beyond the mouth of Snake River. This broad part of the Columbia Valley is largely structural, the basalt dipping below the bottom of the river channel. But near Hanford two large hills of basalt stand in the gravel plain (Fig. 7). They are parts of the north limb of an anticline which pitches eastward beneath the valley from the high basalt hills to the west. Gable Butte rises 763 feet A.T., or about 250 feet above the plain. Gable Mountain has two summits, one of them 1,075 feet A.T., the other 1,116, and the plain surrounding the mountain is as low as 425 feet A.T. Both hills have been greatly scoured and carry the scabland type of knobs and channels. The channels cut across the summits and vary in depth from 50 feet to 150 feet. Trenching the surface of the gravel plain about the base of the hills are much larger channels. They flank the hills in such a fashion that it is clear that the waters which scoured the hills developed the margining channels. The surface of the Spokane flood, therefore, rose above 1,100 feet in this wide valley.[1]

[1] Olaf Jenkins, in *Bull. 26, Div. Geology, Dept. Conservation and Development, State of Washington*, notes that the channels in the plain record a great glacial stream in the valley.

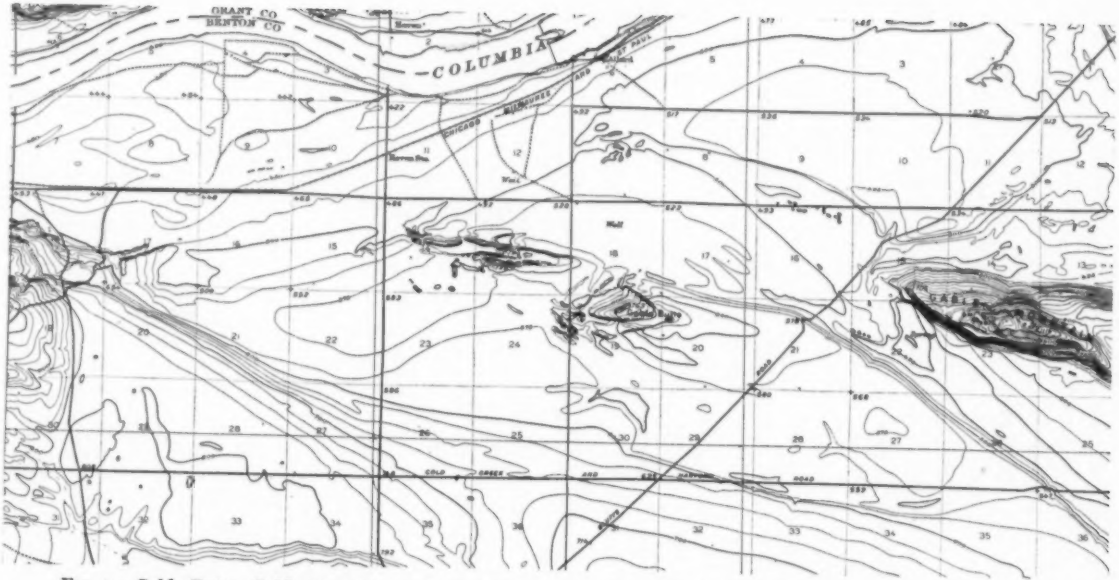

FIG. 7.—Gable Butte, Gable Mountain, and associated channels in the flanking gravel deposits. From the Coyote Rapids, Washington, topographic map, U.S. Geological Survey.

That the gravel plain flooring the wide valley is a deposit of this stream is not clear. Its surface is greatly obscured by sand dunes, and of its expression before they grew, only the large channels remain. Its materials include a large percentage of non-basaltic material. Its altitude is far below the surface of the flood. Yet it may be a gravel floor built where the wide valley invited deposition at the bottom of the great stream. If not, it is older than Spokane, rather than younger, as its trenching shows.

Othello Channels distributaries.—At the east end of Saddle Mountain, near Othello, part of the scabland flood on the plateau spilled southward over a pre-Spokane divide and took several distributary courses thence to both Snake Valley and Columbia Valley. At least four channels seem to have carried glacial water to the Columbia,[1] the northernmost entering in the latitude of White Bluffs and the southernmost mouthing at Ringold. Two of these open on the brink of the Columbia bluffs at 200 and 300 feet above the river, and two open back from the brink at altitudes of about 400 feet above the river, or 750 feet A.T. All of these altitudes are much below the upper limit of the flood as indicated by the rock terrace just north of "The Potholes" (1,200 ft. A.T.) and the summit of Gable Mountain (1,116 ft. A.T.). All are eroded in the weak Ringold silt and clay, which here constitutes the east bluff of the Columbia.

The relations of these channels and Gable Mountain seem to indicate the same situation as at "The Potholes": an initial great depth of water in Columbia Valley, and the lowering of that water-level while the scablands were being eroded. The differences in altitude of the channel mouths seem to indicate abandonment of some during the lowering of the Columbia and continued deepening of the remaining ones until the close of the episode. The gravel deposit at the mouth of Moses Coulee likewise records a late stage in the episode.

It is now in order to seek for the cause of the rapid lowering of the flooded Columbia during the Spokane epoch.

[1] Only the southern two were mapped in "The Channeled Scablands of the Columbia Plateau."

[*To be continued*]

EARTH MOVEMENTS ACCOMPANYING THE KATMAI ERUPTION

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INTRODUCTION

At the time of the eruption of Mount Katmai in June, 1912, earth movements occurred, some of which appear to have been of a character not often observed in connection with volcanic eruptions. Though all were probably related in some manner to the eruption, the manifestations were of several different forms.

The field studies of the Katmai region made by the present writer were conducted during the summers of 1919 and 1923. In 1919 the work was carried on in co-operation with an expedition of the National Geographic Society of Washington, to which three members of the staff of the Geophysical Laboratory were attached. In 1923 a continuation of the studies was rendered possible through the courtesy of the United States Geological Survey. Arrangements were made by which the writer was enabled to accompany one of the parties working in this part of the Alaska Peninsula, and by means of the assistance thus kindly provided, access to this difficult region was very greatly facilitated. In this second visit much additional information on various matters connected with the eruption was obtained. In certain minor matters previous views were modified

by the later studies, but not in a manner to affect important conclusions; rather were these strengthened.

In considering the phenomena that form the subject of this paper the presentation and discussion naturally fall into two parts. In Part I we shall take up the earthquakes known from observation to have accompanied the eruption, and inquire into their general nature. In Part II we shall make a study of the localized fissuring found in the Valley of Ten Thousand Smokes and attempt to ascertain its cause. An inquiry will also be made as to whether the formation of these fissures was responsible for the earthquakes described in Part I.

PART I. REGIONAL EARTHQUAKES

CONTEMPORARY OBSERVATIONS IN ADJACENT REGIONS

It is desirable to give at the outset a brief record of observations made at the time of the eruption, in so far as they have a bearing upon the matters to be discussed. Most of the available information of this kind was collected by G. C. Martin[1] and R. F. Griggs,[2] but other sources of information, which will be mentioned, have been utilized.

Soon after reports of the eruption were received and its magnitude was recognized, Martin was sent to the region by the National Geographic Society. His facilities did not enable him to approach nearer to the volcano than the shores of Katmai Bay, but he was able to get in touch with people who had observed the eruption and its effects, and has recorded the events described by them. This information, collected at a time when events were still fresh in mind, is of great value. Griggs has supplemented this with other data which he was able to collect during later expeditions.

According to the information gathered by these writers, Mount Katmai and the neighboring volcanoes had been quiescent for a long period of years, though disturbances which may, perhaps, be interpreted as a hint of developing activities, are recorded in Spurr's

[1] G. C. Martin, "The Recent Eruption of Katmai Volcano in Alaska," *Nat. Geog. Mag.*, Vol. XXIV (1913), pp. 131–81.

[2] R. F. Griggs has published numerous papers relating to the Katmai region, in the *National Geographic Magazine* and the *Ohio Journal of Science*. These have been collected and published in amplified form in *The Valley of Ten Thousand Smokes*. Washington, D.C.: National Geographic Society, 1922.

account of his trip through the region in 1898.[1] Spurr's party traveled up the valley later known as the Valley of Ten Thousand Smokes, and crossed Katmai Pass. He says:

> Extensive hot springs emerge from the Katmai side of the mountains below the pass, and there are very frequent earthquakes and other evidences of volcanic activity. Our party itself experienced a slight earthquake just after crossing [the pass].

He has recorded also: "One of these volcanoes is said by the natives to smoke occasionally."[2]

Martin's account continues: "Earthquakes were felt at Katmai [village] for at least five days prior to the eruption, while more severe shocks were felt on June 4 and 5 at Kanatak, Uyak, and Nushagak." These places are distant 59, 56, and 131 miles from Mount Katmai to the southwest, southeast, and west-northwest, respectively.[3] Reports show clearly that shortly before and during the eruption earthquakes of considerable violence were felt at widely separated points. These have naturally been attributed to the activities of the volcano itself, but evidence to be presented indicates that not all were of this origin.

According to Martin, the volcano probably began to throw out large volumes of gas on the fifth of June, as observers at Cold Bay (about 40 miles to the west of south) noted that the northern sky looked black and stormy late that night,[4] though the weather on the coast was fair. From our later information it seems probable that this cloud was not from Katmai crater, but was due to the outburst of the great sand-flow in the Valley of Ten Thousand Smokes. We know now that the sand-flow, at least in great part, antedated the eruption of Katmai,[5] and the ash cloud that accompanied it should have been visible at a great distance.

[1] J. E. Spurr, "A Reconnaissance in Southwestern Alaska in 1898," *U.S. Geol. Surv., 20th Ann. Rept.*, Part VII (1900), p. 92.

[2] J. E. Spurr, *op. cit.*, p. 232.

[3] Most of the distances given in this paper have been calculated by the appropriate formula from the latitude and longitude of the places. In a few cases, where the reference is to a somewhat indefinite point in an area, the distances have been scaled.

[4] At this time of the year there is almost no darkness throughout the twenty-four hours.

[5] R. F. Griggs, *op. cit.*, p. 255; C. N. Fenner, *The Origin and Mode of Emplacement of the Great Tuff Deposit of the Valley of Ten Thousand Smokes*, pp. 25–31. Washington, D.C.: National Geographic Society, 1923.

On the morning of June 6 there seem to have been frequent minor explosions and earthquakes, though it was only at Seldovia (144 miles to the northeast) and Nushagak (131 miles to the west-northwest) that these were noted. Early in the afternoon of June 6 the volcano passed into a state of violent eruption. The beginning of the violent phase was apparently at 1:00 P.M., June 6, at which time a terrific explosion and earthquake were noted at Cold Bay, and at the same time a heavy cloud rising over Mount Katmai was seen from the steamer "Dora," 55 miles to the east across Shelikof Strait. At 3:00 P.M. there was a second tremendous explosion,

> heard for hundreds of miles around, and the volcano passed into a state of continuous eruption, which lasted, except for possible short intervals, for several days. This explosion was noted at Uyak, at Iliamna Bay, at several places on Iliamna and Clark lakes, at Koggiung, and at a point 90 miles southwest of Eagle.

At about the same time (exact hour not noted) explosions were heard at Juneau, 745 miles to the east, and at Fairbanks, 513 miles to the north-northeast.

After the outbreak at 3:00 P.M., according to Martin, the activity became somewhat less. The next violent explosion was probably about 11:00 P.M. At about that time a severe earthquake was noted at Cold Bay and a strong glare of light at Kanatak, a few miles farther to the southwest. At Kodiak (102 miles to the east-southeast) a number of severe earthquakes were reported during the night of the sixth. On June 7, Father Patellin at Kanatak (59 miles south of west from Katmai) noted earthquakes nearly all day, with short intervals between. Many of them were strong, and there was continuous rumbling. That evening after ten o'clock came the strongest earthquake, accompanied by heavy rumbling and rock-slides from all around. There seems to have been a strong glare of light from the volcano, for it was recorded that "the mountains were like sunshine." After midnight he heard "a big noise like thunder from the Katmai side," after which everything was quiet. At Iliamna Bay (104 miles to the north-northeast) earthquakes lasted throughout the night of the seventh, and it was said that the earth never ceased to move for nearly twelve hours. At 2:00 A.M. on the eighth, cannonading at irregular intervals was heard at Cordova, 362 miles east-northeast. This may have been due either to explosions or to

earthquakes. Earthquakes were reported from 90 miles southwest of Eagle (probably 500 miles or more to the northeast of the volcano) at 11:00 P.M., June 6 or 7. During a period of several hours at about midnight of the seventh, both volcanic and seismic disturbances seem to have reached a climax of violence.

On June 8 there seems to have been an abatement, though considerable activity persisted. At Cold Bay (40 miles to the southwest) records of earthquakes and explosions were kept from June 6 to August 15. On fifty of the seventy days from June 8 to August 15 earthquakes were recorded. The most severe were on June 11 and 21 and on July 30. On August 17 an earthquake at Naknek (about 76 miles to the west-northwest) was said to have been so strong as to upset lamps on a table.

On June 8 the Parker-Browne mountaineering expedition, engaged in the ascent of Mount McKinley, 350 miles or more to the northeast, heard deep, booming noises, which lasted all day and which they attributed at the time to movements of the glacier on which they were camped. Later they believed them to have been reports from the Katmai explosions. Since, however, information from near Mount Katmai indicates that the greatest violence of the eruption had passed by that time, mild earthquakes may have been the source, though this is not certain. On July 6 the same party, then at the northern base of Mount McKinley, experienced an undoubted earthquake of great violence. The earth heaved and rolled, and the country far and near was scarred with landslides.[1]

A short report of observations made at Seldovia during the eruption of Mount Katmai was submitted to the Coast and Geodetic Survey by I. M. Dailey, assistant, and a copy of the manuscript has been kindly furnished me by Colonel E. Lester Jones, director of the Survey. The features of the account that are pertinent here are as follows:

During the morning of June 6 low, deep reports as of distant blasting were heard, and some people even then believed them to be volcanic. As the day passed the reports came oftener and louder, and continued all day. The next morning there was a light fall of

[1] Belmore Browne, *The Conquest of Mount McKinley*, pp. 323 and 356. New York, 1913. For an account of the effects visible at Mount McKinley a year later, see Hudson Stuck, *The Ascent of Denali*, pp. 40 and 41. New York, 1914.

volcanic ashes. No mention of explosions on June 7 or June 8 is made, but on June 9 the explosions are spoken of as continuing at irregular intervals. There were ashfalls also. Explosions at intervals all of June 10 are noted, but none were heard on June 11. There was no ordinary thunder and no lightning at Seldovia.

CHARACTERISTICS OF VOLCANIC AND TECTONIC EARTHQUAKES

The accounts that have been presented summarize the chief features of the eruption as noted at the time, in so far as they are concerned with earth shocks and related phenomena. It is evident that during the eruption and for some time afterward shocks of various degrees of intensity affected near and distant points. Some of the tremors and even stronger shocks felt at localities not far distant from the volcano might belong in the class of volcanic earthquakes. Others, however, were felt at such distances that something more seems to be demanded. Our first inquiry, therefore, will be directed toward determining whether at the time of the eruption true tectonic movements affected the region.

If such was the case the association is unusual. Milne[1] says that

> although in many countries there may be displays of volcanic and seismic activity taking place almost side by side, it is only rarely that there is direct relationship between the two. . . . . This is true even for the largest and most violent eruptions, when mountains have with practically a single effort blown off their heads and shoulders. Thus the earthquake which accompanied the eruption of Bandaisan, in central Japan, in 1888, was felt only over a radius of 25 miles.

Davison[2] divides earthquakes into two main classes: tectonic and volcanic; and the latter again into two kinds, (1) those which are purely volcanic in their origin, and (2) those which are of tectonic origin in so far as they are due to the growth of faults, but of volcanic origin in that the slips are precipitated by present or past volcanic operations. The latter are, as a rule, not coincident with volcanic eruptions, but precede or follow them and only rarely accompany them, but a remarkable exception is noted in the earthquakes accompanying the outbreaks of Sakura-jima, Kirishima-yama, and Iwo-jima in Japan in 1914.

[1] J. Milne, "Earthquakes," *Encyc. Brit.*, Vol. VIII (11th ed.), p. 821.

[2] Charles Davison, *A Manual of Seismology* (1921), pp. 215 ff.

When three volcanoes situated as these are and all of infrequent activity, burst into eruption so nearly together, and when two of the eruptions are accompanied by strong and deeply-seated earthquakes, it is difficult not to regard both phenomena as different manifestations of a common cause, namely, the gradually growing stresses along the whole volcanic chain. But there is no reason for supposing that the earthquakes result from the volcanic operations. They should therefore be considered as tectonic, and not as volcanic, earthquakes.[1]

Moreover, purely volcanic earthquakes possess characteristics which differentiate them sharply from tectonic earthquakes.

No feature of volcanic earthquakes is so marked and none so significant as the smallness of the disturbed area, considering the great intensity of the shock at the epicenter. We may have an earthquake, like that of Nicolosi in 1901, destroying houses within a minute meizoseismal area, and yet imperceptible at a distance of more than 4 miles, or one like that of Fondo Macchia in 1865, causing utter ruin over an area of 5 square miles and yet not felt outside an area of more than 113 square miles, or, again, one like that of Ischia in 1883, leveling every building within an area of 3 square miles, and only just perceptible at a distance of 20 miles from the epicenter.[2]

From these quotations two facts stand out clearly. The first is that only rarely do tectonic earthquakes accompany volcanic eruptions, though instances are known; and the second is that a volcanic earthquake diminishes very rapidly in violence from the epicenter outward. From this latter circumstance we are led to expect that if the very perceptible shocks felt at considerable distances during the Katmai eruption were of volcanic origin, the destructive effects in the immediate vicinity of the volcano should have been of great intensity. During my two visits to the Katmai region, in 1919 and 1923, the terrain was examined with this idea in mind.

FIELD OBSERVATIONS NEAR MOUNT KATMAI INDICATE LACK OF VIOLENT EARTHQUAKES

At our first landing place on the beach in 1919, just south of Katmai Bay and about 17 miles south of Mount Katmai, cliffs of sedimentary strata, perhaps 100 feet in height, showed many blocks of rock hanging loosely and evidently undisturbed for years. Later, while we were encamped on the shore of Naknek Lake, a mountain

[1] See also an article on "Volcanic Earthquakes," by the same writer, in *Jour. Geol.*, Vol. XXIX (1921), p. 97.

[2] Charles Davison, *op. cit.*, p. 225.

just to the south was ascended (height a little over 4,800 feet above the sea and practically the same above the lake). At the top the western and northwestern faces were found to present an extremely precipitous scarp for several hundred feet, evidently the upper portion of an old glacial cirque. The summit rock consisted of dense hornblende andesite-porphyry, and was in a greatly shattered condition as a result of the opening up of intersecting joints through frost action. There were quantities of rock in precarious positions, both in place and on the steep talus slopes of the cirque cliffs, which would seemingly be dislodged by even gentle earthquake shocks. This mountain is about 21 miles northwest of Mount Katmai.

About 13 miles northwest of the volcano a mass of columnar basalt (probably an ancient volcanic neck) showed among its cliffs many loose columns apparently just ready to give way and fall. These last two occurrences are even nearer to the Valley of Ten Thousand Smokes than they are to Mount Katmai, and indicate even more strongly that the outbursts in the valley, later to be discussed, did not give rise to violent earthquakes a few miles away.

In 1923 similar occurrences of masses of rock hanging loosely on cliffs were noted on the southern flanks of Mount Katmai itself. They are so near the focus of eruption as to appear of special significance. Such occurrences were seen in the deep, narrow canyon from which issued the flow of pumice and ash that Griggs has called the Katmai mud-flow. This locality is about $2\frac{1}{2}$ miles from the edge of the crater.[1] In places the walls of the canyon are nearly vertical, and probably 500 feet high. The general rock is a dense andesite, often of very platy structure. The precipitous walls of this narrow gorge appear loose in many places, and in a condition such that large masses of rock should be easily dislodged (Fig. 2).

A little to the east and east-northeast of here the canyon of Katmai River is bounded by high cliffs. On the southeast side are the sediments of the Barrier Range, and on the northwest are the dark crimson and gray lava flows of Mount Katmai. At the place shown in Figure 3, the tops of cliffs in the foreground on the left, at the brink of the chasm, are composed of quantities of shattered, platy andesite, large amounts of which look ready to fall. That there has been no

[1] For position consult the accompanying map (Fig. 1).

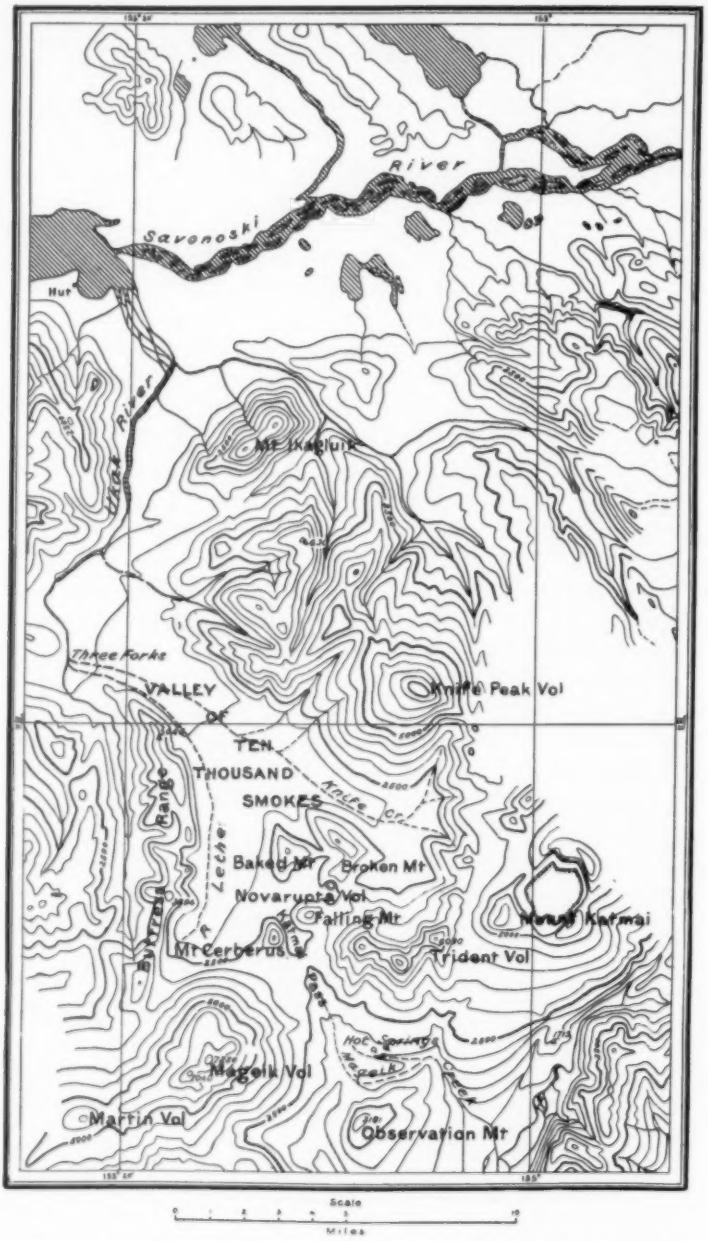

FIG. 1.—Map of the Valley of Ten Thousand Smokes and vicinity, from drawings of the Kachemak-Katmai map of the U.S. Geological Survey, based on surveys of the U.S. Geological Survey and the National Geographic Society. Contour interval 500 feet.

recent rock-fall of importance here is shown by the fact that just below these cliffs more gradual slopes carry dead bushes (killed by the eruption) and fresh grass. In general, the material in the cliffs at

FIG. 2.—Steep-walled gorge on southern flank of Mount Katmai. Abundance of loose rock in walls and on slopes indicates lack of recent severe earthquakes. (Photo by C. N. F., 1923.)

the brink of the narrow gorge is shattered rock in precarious position.

Numerous other occurrences were noted and might be cited. There may be a query whether the relations might not be explained by supposing that severe earthquakes had shaken down the outer

faces of cliffs, leaving the inner portions in the shattered condition in which we see them. The evidence is opposed to this. In the last case cited, for instance, the evidence is very positive that no important rock-fall has occurred, and in other cases it is almost equally strong. In general, the appearance of the loosely hanging cliff faces is that normally produced by the slow operation of atmospheric agencies in opening up joint cracks. The presence of perched blocks and loosely supported columns gives further confirmation. The general conclusion drawn was that no shocks of major violence disturbed the region during the eruption. In many places the relations are of such a character that it is difficult to understand how they could have survived even moderate shocks, but that such occurred is shown by other phenomena.

At a number of places in the region recent bowlder flows or landslides, of considerable magnitude, have been discovered. The exact date of occurrence of these cannot be definitely fixed, but it is fairly certain that most of them, if not all, were closely associated with the eruption.

These landslides, when set in motion, seem to have acted in a similar manner to others which have been described in the literature, such as that of Bandai-san,[1] in Japan; that of Frank,[2] in Alberta; and that of Elm,[3] in Switzerland. The essential conditions leading to movement seem to be the presence of a mass of fragmental material, resting in such a position that it may easily be set in motion. When such a mass is dislodged from a height and precipitates itself down a steep gradient, it behaves astonishingly like a liquid, even when it flows out on a gentle slope, though it may be made up largely of bowlders. Its consistency appears to resemble that of a concrete batter.

One of these Katmai landslides, called by Griggs the "Mageik landslide," has been described in detail by him.[4] His investigations

[1] S. Sekiya and Y. Kikuchi, "The Eruption of Bandai-san," *Jour. Col. Sci., Imp. Univ. Japan*, Vol. III, Part II (1889), pp. 91–172.

[2] R. G. McConnell and R. W. Brock, *Report on the Great Landslide at Frank, Alberta, 1903; Ann. Rept. Dept. Int., Can.* (1903), p. 10.

[3] E. Buss and A. Heim, "Der Bergsturz von Elm," *Zs. Deutsch. Geol. Gesell.* (1882), pp. 74 and 435.

[4] R. F. Griggs, *op. cit.*, pp. 135–45. In 1919 I was able to visit the lower part of this slide, and to observe some of the remarkable features that Griggs describes, but I did not see the place where it originated.

showed that at the time he studied it parts of the slide were covered with Katmai ash, and other parts were free of it—a rather puzzling circumstance in attempting to fix its date; but his view

FIG. 3.—Cliffs on brink of canyon of Katmai River. In the foreground, quantities of loose rock in place and on slopes show lack of severe shocks during the eruption, while just beyond is shown the place from which a great landslide started. (Photo by C. N. F., 1923.)

is that the movement probably took place about the time of the eruption.

The material started at a cliff of disrupted lava and sandstone at the head of a valley, but the evidence regarding the nature of the

forces that set the mass in motion is not easy to interpret. Griggs says:

> Closely adjacent to the part of the cliff that fell away, colossal columns several hundred feet high are still hanging, apparently so ready to topple over that one wonders how they survived the shock that set off their neighbors.

This landslide occurred about 12 miles southwest of Katmai crater.

A similar flow, but of smaller mass, is to be seen at the place where the canyon of Mageik Creek discharges into the valley of Katmai River, 5 or 6 miles south of Katmai crater. Here great bowlders,

FIG. 4.—Bowlder flow from the canyon of Mageik Creek, spreading out over the floor of Katmai Valley. The mass was presumably set in motion by earth movements during the eruption. (Photo by C. N. F., 1923.)

many of them 6 feet in diameter, mixed with gravel and sand, were spread along the lower part of the canyon, and were carried out into the open valley beyond, covering a wide area of very gentle slope (Fig. 4). The source of the material has not been searched for. As most of the bowlders and gravel are well rounded, and as they consist of a variety of rocks, they had probably formed a secondary deposit before the flow occurred. The time of movement was after the pumice ejections from Katmai.

Other flows or slides described by Griggs are the Katmai slide, which dammed Katmai Canyon, and caused, when it broke, the

flood that occurred just before Griggs's first visit to the region in 1916; and the Noisy Mountain slide, which issued from a side valley, farther up Katmai River. These last two apparently antedated the eruption. The Katmai slide is of interest in that it originated from the breaking away of a large section of cliff close to the shattered face shown in Figure 3. Evidently the shocks that caused these large masses of rock to let go were not sufficient to shake down the all-but-detached portions of the neighboring cliffs.

These phenomena appear somewhat contradictory in their implications, and it is not easy to form an estimate as to the severity of the shocks denoted by them. In the commonly used Rossi-Forel scale of earthquake intensity, as revised and simplified by the Investigation Commission of the California earthquake,[1] the more severe effects are graded as follows, in increasing intensity:

VII. Violent shock, overturning of loose objects; falling of plaster; striking of church bells; some chimneys fall
VIII. Fall of chimneys; cracks in the walls of buildings
IX. Partial or total destruction of some buildings
X. Great disasters; overturning of rocks; fissures in surface of earth; mountain slides

These effects relate chiefly to edifices of human construction, and the criteria are therefore lacking in the region under consideration. As near as comparison may be made, it seems that a shock severe enough to overthrow chimneys or even to cause the fall of plaster would have been sufficient to dislodge many of the loosely hanging rocks seen near Mount Katmai. On the other hand, the formation of fissures and the occurrence of mountain slides are associated in the scale with maximum shocks; but on this point the Commission makes some very pertinent comments. Their *Report* says:

> Finally in grade X of the scale, fissures in the ground are taken as a criterion of the highest grade of intensity, when in reality such fissures have under different conditions very different values from this point of view. The fissures which extend down into the earth's crust, and are due to its actual rupture on a fault-plane, are of course significant of the highest degree of disturbance usually experienced in earthquakes; but those cracks and fissures which occur in valley bottoms, due to the slumping of soft material toward the stream trench, or those

[1] "The California Earthquake of April 18, 1906," *Report of the State Earthquake Investigation Commission*, Vol. I, p. 161. Washington: Carnegie Institution of Washington, Pub. No. 87, 1908.

cracks which are associated with landslides, in those cases where the landslide was imminent and was merely precipitated by the earth jar, are superficial phenomena and do not necessarily indicate so high a degree of intensity as that marked X on the scale.[1]

This is evidently sound reasoning, and indicates the necessity of caution in drawing inferences on severity from landslides. If, however, we eliminate the consideration of landslides, we have no other visible indication of shocks; but this elimination would be obviously unfair. The number of landslides indicates disturbances of some severity at least, but they were not so strong but that many loose rocks were left hanging, and were not at all of the magnitude that would be expected if the shocks felt at distant points were solely of volcanic origin with the crater as the center of disturbance. As we have already seen, a characteristic of volcanic earthquakes is very rapid decrease of intensity from the center outward. Davison says: "In volcanic earthquakes, strong enough to ruin the epicentral villages, the area [of sensible disturbance] ranges from 50 to about 1,000 square miles,"[2] corresponding to radii of 4 and 18 miles, respectively. This is doubtless related to the fact that "the more rapid the decline outwards in the intensity of the shock, the less is the depth of the focus."[3]

From the phenomena described we may draw the tentative inference that the earthquakes felt at distant points were not the direct result of volcanic disturbances emanating from Mount Katmai or from its immediate neighborhood. We are then led to inquire whether there is evidence that tectonic movements affected the region. The data that will be presented indicate that such was the case, and that these movements probably originated at a number of somewhat widely separated points.

EVIDENCE OF TECTONIC EARTHQUAKES

The chief source of information used is the compilation for 1912 of the well-known seismological tables which the late Dr. Otto Klotz issued for several years.[4] These are based upon the records of

[1] *Op. cit.*, p. 162.

[2] Charles Davison, *op. cit.*, p. 50. [3] *Ibid.*, p. 133.

[4] Otto Klotz, "Location of Epicentres for 1912," *Jour. Roy. Astronom. Soc. of Can.*, Vol. VII (1913), p. 229.

most of the first-class observatories of the world (though not all of this class are included), and probably represent the best available information on the matter in question for one who is not a specialist in seismology. They show the epicenters of those earthquakes of the year whose positions can be calculated, together with others whose data do not yield satisfactory determinations of epicenters.

Klotz's compilations have been supplemented to some extent by other data. Professor J. B. Woodworth, in charge of the Seismographic Station at Harvard, has, at my request for information, very kindly supplied me with a copy of their monthly *Bulletin* for June and for those parts of July and November, 1912, in which Alaskan earthquakes are recorded. Professor Bailey Willis, of Leland Stanford University, has kindly obtained from Father Jerome S. Ricard, S.J., a report showing that seismic disturbances were recorded at Santa Clara, California, on May 6, June 7, and June 9, 1912, which were believed to be of Alaskan origin. Father Francis Tondorf, S.J., Georgetown University, Washington, was so good as to look up his records, and report that in the case of all the quakes recorded at about the date of the eruption the amplitudes were very large. The calculated distances had been found to fit, approximately at least, the distance to Alaska, and there seemed to be no doubt of a connection between the eruption and the tectonic quakes recorded.

In Table I the principal data are assembled in parallel columns, showing in one case the disturbances noted by direct observation at the time of the eruption, and in the other case the effects produced at distant seismographic stations. For convenience of comparison, the Greenwich mean time in which stations record their observations has been changed to standard time of the one hundred and fiftieth meridian, west, by subtracting ten hours. The symbols ϕ and λ have their usual significance of latitude and longitude. For Katmai $\phi = 58°15'$ N., $\lambda = 155°$ W.

Klotz's determination of epicenters, included in the second column of Table I, is made by the usual method of triangulation. The intersection of three or more arcs at or near a common point gives an epicenter. In some cases a point thus determined from one set of stations may differ considerably, even several degrees, from another point similarly determined from other stations. As Klotz points out,

TABLE I

COMPARISON OF LOCAL OBSERVATIONS WITH RECORDS OF DISTANT SEISMOGRAPHIC STATIONS

(Time given is that of the 150th Meridian, West)

Local Observations	Records of Distant Stations
1912	
	Jan. 4. Seismic records of Aachen, Hamburg, Manila, Ottawa, and Pulkowa give $\phi = 50°40'$; $\lambda = 179°54'$ E. Galitzin's calculations give $\phi = 49\frac{1}{2}°$; $\lambda = 175°$ E. Zeissig's calculations give $\phi = 50\frac{1}{2}°$; $\lambda = 176°$ W. The epicenter falls in or near the western Aleutian Islands
Jan. 31. Heavy earthquake shocks felt throughout southwestern Alaska (according to Klotz)	Jan. 31. Cartuja, Göttingen, Hamburg, Ottawa, Pulkowa, St. Louis, Strassburg, Zi-ka-wei, give $\phi = 60°00'$; $\lambda = 146°36'$ W.
	May 6. At Santa Clara, California, a tremor recorded, thought to be of Alaskan origin
June 1–6. Earthquakes at Katmai village (14 miles south of volcano)	
June 4–5. Severe shocks at Kanatak (59 miles SW.), Uyak (56 miles SE.), and Nushagak (131 miles WNW.)	
June 6, morning. Frequent minor explosions and earthquakes noted at Seldovia (144 miles NE.) and Nushagak (131 miles WNW.). Probably about this time the fissures in the Valley of Ten Thousand Smokes opened and the incandescent sand flow was poured out	
June 6, 13 hr. Terrific explosion and earthquake noted at Cold Bay (40 miles SW.); smoke cloud seen from steamer "Dora" (55 miles E.), rising over Mount Katmai. Probable beginning of violent phase of eruption, continuing until June 8	June 6, 12 hr. 41 min. Seismic shock recorded at Seattle Observatory, according to press report
June 6, 15 hr. Second tremendous explosion heard for hundreds of miles around	June 6, from 18 hr. 5 min. to 23 hr. 45 min. Seismic shocks at Harvard, of unknown origin

TABLE I—*Continued*

Local Observations	Records of Distant Stations
1912	
June 6, 23 hr. Severe earthquake at Cold Bay (40 miles SW.), and a strong glare of light seen from Kanatak (59 miles SW.)	June 6, 24 hr. (1) Seismic records ar Harvard, Irkutsk, Ottawa, and Pulkowa give $\phi = 58°24'$; $\lambda = 152°45'$ W. (2) Records of Cartuja, Pulkowa, and Zi-ka-wei give $\phi = 58°10'$; $\lambda = 161°15'$ W.
June 6. During the night, a number of severe earthquakes at Kodiak (102 miles ESE.)	
June 7. Earthquakes noted all day at Kanatak (59 miles SW.)	June 7, from 1 hr. 02 min. to 9 hr. 12 min. A series of merging seismic shocks at Harvard, known to be of Alaskan origin
	June 7, 2 hr. Ottawa, Pulkowa, and Zi-ka-wei give $\phi = 57°40'$; $\lambda = 157°40'$ W.
	June 7, 8 hr. (1) Strassburg, Tiflis, Vienna, and Zi-ka-wei give $\phi = 58°42'$; $\lambda = 142°40'$ W. (2) Cartuja, Irkutsk, and Tiflis give $\phi = 56°56'$; $\lambda = 159°00'$ W.
	June 7, 12 hr. Seismic shock at Georgetown Observatory (Washington, D.C.)
	June 7, 21 hr. Cartuja, Harvard, Ottawa, and Pulkowa give $\phi = 57°56'$; $\lambda = 154°00'$ W.
June 7, 23 hr. Strong earthquake, with heavy rumbling, rockslides, and glare of light, at Kanatak (59 miles SW.). After midnight a noise like heavy thunder from the direction of Katmai	June 7, 23 hr. 13 min. Seismic shock at Harvard
June 7, evening, to June 8, morning. Severe earthquakes at Iliamna Bay (104 miles NNE.)	
June 6 or 7, 23 hr. Earthquakes reported 500 miles to northeast of Katmai	
	June 8, 0 hr. 26 min. Seismic shock at Harvard
	June 8, 0 hr. 54 min. Seismic shock at Harvard
June 8, 2 hr. Cannonading heard at Cordova (362 miles ENE.)	
June 8. Eruption of volcano continuing, but with lessened violence	June 8, 3 hr. Irkutsk, Pulkowa, and Strassburg give $\phi = 57°58'$; $\lambda = 152°03'$ W.

TABLE I—*Continued*

Local Observations	Records of Distant Stations
	1912
June 8. Rumblings (possible quake) heard at Mount McKinley (350 miles NE.)	
June 8–Aug. 15. Shakings at Cold Bay nearly every day	
June 9. Reports from Kaflia Bay (26 miles E.) indicate continuance of eruption. Explosions heard throughout the day at Seldovia (144 miles NE.)	June 9, 7 hr. 42 min. 12 hr. 05 min. 12 hr. 37 min. } Seismic shocks at Harvard
	June 9. Irkutsk, Ottawa, and Pulkowa give $\phi = 56°48'$; $\lambda = 156°33'$ W.
	June 10, 6 hr. 15 min. to 7 hr. 57 min. Seismic shocks at Harvard, known to be of Alaskan origin.
	June 10. Aachen, Harvard, Irkutsk, Ottawa, and Pulkowa give $\phi = 57°02'$; $\lambda = 154°30'$ W.
June 11. Earthquake at Cold Bay	June 11, 21 hr. Data indicate an epicenter at approximately $\phi = 57.7°$; $\lambda = 149.3°$ W.
	June 17. Galitzin's calculations give $\phi = 57°$; $\lambda = 149.7°$ W.; confirmed approximately by data from Pulkowa and Vienna
June 21. Earthquake at Cold Bay	
July 6. Very severe earthquake at Mount McKinley (350 miles NE.)	July 6, 22 hr. to July 8 (no time given). Many stations record severe shocks, calculation of whose epicenters gives origins near Mount McKinley
July 30. Earthquake at Cold Bay	
Aug. 17. Earthquake at Naknek (76 miles WNW.)	
	Oct. 12. Irkutsk, Pulkowa, Tiflis, and Vienna give $\phi = 50°24'$; $\lambda = 178°45'$ E. (Just south of western Aleutian Islands)
Nov. 6 or 7. Quake reported at Seward (234 miles NE.).	Nov. 6, 22 hr. Reports from thirteen stations give intersections of 1. $\phi = 56°42'$; $\lambda = 156°20'$ W. 2. $\phi = 58°12'$; $\lambda = 153°33'$ W. 3. $\phi = 56°18'$; $\lambda = 150°33'$ W.
	Dec. 5. Reports of shocks from eight stations give $\phi = 57°08'$; $\lambda = 154°15'$ W.

this is necessarily the case from the nature of the data; and he indicates several sources of error, such as uncertainties in the reading of the grams, false interpretation of the grams, and imperfections of velocity tables. Another important factor is that an earthquake itself does not emanate from a point, but from a surface or volume. As a result of these uncertainties, it is often not possible to feel confidence that the location of an epicenter has been determined closer than within 100 miles. Nevertheless, the computed epicenters for the quakes of the period June 6–10 fall so near the Katmai region as to make it appear certain that during the eruption a number of tectonic quakes emanated from one or more foci not far distant from the volcano, and produced world-wide tremors. It does not appear possible to decide satisfactorily how close to the mountain the foci were. The epicentral determinations from distant stations are not sufficiently exact for the purpose, and the evidence on the ground is inconclusive. As already noted, several rock avalanches are known to have occurred immediately adjacent to the mountain itself, and one about 12 miles to the southwest. Even at Kanatak, 59 miles to the southwest, rock slides were reported, and severe shocks at a number of distant points. There are vast stretches of territory where avalanches might have occurred, but which are unexplored. During the journey to the valley from Cold Bay in 1923, a number of places along the route were seen where minor landslips had taken place within a few years, but their relation to the events of 1912 is problematical. The most that can be said safely on the general problem is that quakes of tectonic character were associated closely in point of time with the eruption, and rather closely in point of space. The relation that the fissuring in the Valley of Ten Thousand Smokes bears to the question is important, but its discussion is best deferred to later pages.

The movements during the eruption had been preceded in January by a quake in or near the western Aleutian Islands and one in the Prince William Sound region. After the intensity of the eruption subsided, recorded quakes continued to emanate from the Katmai region for several days. On July 6 there was a severe earthquake near Mount McKinley, far to the northeast. On November 6 and December 5 there were movements whose computed epicenters were

near Kodiak Island. During 1913 and 1914 there are records of further movements in the middle and western Aleutian Islands.

THE ERUPTION AND QUAKES OCCURRED IN A ZONE OF STRUCTURAL INSTABILITY

It cannot be said with certainty that all these movements were causally related, but the points of origin lie within a comparatively narrow zone of distinct characteristics, which would, with little hesitation, be considered of close structural relationship. During the year no important quakes outside of this zone for great distances are noted by Klotz.

Moreover, the features of the zone are those held to be characteristic of earthquake belts. Davison expresses the principle as follows:

> The most important law of seismic distribution is that earthquakes are as a rule strongest and most frequent in those portions of the earth in which the average slope of the ground is greatest;[1]

also:

> In . . . . groups of islands arranged in the festoon form, such as Sumatra and Java and the Aleutian Islands, or in mountain chains like the Himalayas and those of Alaska, ... the steep convex side is visited by more frequent and more violent earthquakes than the gently sloping concave side.[2]

In a minor point Davison, in the foregoing quotation, is in error. The slope on the concave side of the Aleutian festoon, as well as on the convex side, is very steep. There seems to be a common impression that the whole of Bering Sea is shallow; on the contrary, a great area lying to the north of the Aleutians, from Unalaska Island westward, is very deep.[3]

The Aleutian Islands, throughout most of their length, form the summits of a remarkably narrow and steep ridge, which drops to abyssal depths on each side. Its northeastward continuation forms the Alaska Peninsula, which is bounded by a shallow sea on the northwest, but on the southeast side the shelf drops abruptly to depths of 1,000–2,000 fathoms at a distance of 50–125 miles from the coast. The edge of the shelf is most distant from the peninsula in the vicinity of Kodiak Island. This is a mountainous mass com-

[1] Charles Davison, *op. cit.*, p. 168.

[2] *Ibid.*, p. 172.

[3] See Charts 8802 and 9102 of the Coast and Geodetic Survey. Suess has recognized this fact. See *The Face of the Earth* (Eng. transl.), Vol. IV, p. 349.

posed chiefly of contorted sediments, diorite, and granite,[1] which rises abruptly from the submerged shelf, and suggests a horst.[2]

The island is separated from the peninsula by the shallow waters of Shelikof Strait, whose northwestern shore is formed by moderately high but precipitous mountains, among which the volcanic peaks of Katmai and its neighbors are situated. Beyond the Katmai region the ranges of the Alaska Peninsula continue to the northward. Their termination is conventionally placed in the region lying between Cook Inlet and Lake Clark, which has been little explored but is known to be of high relief.[3] There is, however, no obvious break in continuity at this point, but under the name of the Alaska Range, high and rugged mountains continue several hundred miles in a broad arc, trending first northeastward, then eastward, and finally southeastward, and including the culminating peaks of Mount McKinley and its neighbors. In this region a parallel inner arc is formed by the mountains of Kenai Peninsula and the Chugach Mountains. To this the mountains of Kodiak Island may belong.

Throughout this province the trend lines of major tectonic structure are continuous, or where a second line of mountain axes appears, this is parallel to the first. Brooks applies the term "Pacific Mountain system" to the main mountainous area, and describes this system as

> made up of a number of parallel ranges forming a rugged highland of crescentic outline sweeping around the Gulf of Alaska. Its central part is upwards of two hundred miles in width, but the system narrows to the southeast and to the

[1] Closely folded slates and graywackes make up most of the explored portion of the island. Martin describes old metamorphic schists near Uyak, on the northwestern side (*U.S. Geol. Surv. Bull. 542*, p. 128). Diorite was found by Becker at Karluk, on the northwestern side (*U.S. Geol. Surv., 18th Ann. Rept.*, Part III, p. 41), and granite was reported by him to form "the southern end of the ridge running along the westerly coast" (*op. cit.*, p. 36). Granite or diorite occurs east of Kizhuyak Bay and at the south end of Uganik Island (Martin). In 1923, during a stop by our steamer at the cannery at Alitak Bay, at the southern end of the island, the rocks of the vicinity were found to be coarse quartz-mica diorite. On another occasion the cliffs for several miles near Cape Kuliuk, as seen from the deck of a steamer not far from shore, had the appearance of granite or similar rock. Their light-gray color and massive appearance had a very different look from the dark fissile slates. In lithology and structure Kodiak Island is entirely dissimilar from the Jurassic areas of the adjacent shores of the peninsula. Its relationship seems to be rather with the mountains of Kenai Peninsula.

[2] Suess regards Shelikof Strait and Cook Inlet as having the characters of a fault trough. See *op. cit.*, p. 378.

[3] A. H. Brooks, "The Mount McKinley Region, Alaska," *U.S. Geol. Surv., Prof. Paper 70* (1911), p. 45.

southwest. It is continued to the southeast by the Coast Range of British Columbia, and to the southwest by the rugged Aleutian Islands.[1]

Throughout the zone, from the western Aleutian Islands around into British Columbia, there are abrupt descents from mountains to lowlands, or from the summits of ocean ridges to abyssal depths—conditions favorable for earthquake movements. A rather remarkable feature of the zone is the reversal in direction of curvature of the trend lines in proceeding from the Aleutian Islands to the Alaska Range. The interpretation of this in terms of theories of mountain-building is not evident.

APPARENT COINCIDENCE OF TECTONIC SHOCKS WITH MAJOR OUTBURSTS OF MOUNT KATMAI

A comparison of the data given in the two columns of Table I serves to bring out indications that tectonic earthquakes were almost coincident with some of the greatest outbursts of the volcano, though an element of uncertainty arises because of the difficulty of deciding in all cases just what phenomena observed from afar were indicative of major phases of the eruption. A minor uncertainty is due to the fact that in these out-of-the-way places the accuracy of clocks and watches is not ordinarily of great importance, and the reported time of events may be somewhat in error. The salient features of apparent correlation are as follows:

The first violent explosion on June 6, at thirteen hours, coincided closely with a shock recorded at Seattle, according to the daily press, but not given in Klotz's compilation nor in the Harvard record. The second great explosion on June 6, at fifteen hours, preceded by a few hours shocks received at Harvard, of unknown origin, from eighteen hours, five minutes, to twenty-three hours, forty-five minutes. At twenty-three hours a strong glare of light was noted at Kanatak, and a hard earthquake at Cold Bay. These almost coincided with the first world-wide tremors received at seismographic stations. On June 7, at twenty-three hours, an earthquake, rock slides, and glare of light were noted at Kanatak, followed some time after midnight by heavy noises from the direction of Katmai. These probably denoted another major outburst, and may be correlated with the

[1] A. H. Brooks, "The Physiographic Provinces of Alaska," *Jour. Wash. Acad. Sci.*, Vol. VI (1916), p. 252.

shocks reported by numerous observatories from June 7, twenty-two hours, to June 8, three hours.

This apparent synchronism between great outbursts and tectonic earthquakes is remarkable, but a similar coincidence apparently occurred during the eruption of Sakurajima, in 1914. It will be remembered that this great eruption also was accompanied by tectonic earthquakes, and at least one of these seems to have been nearly simultaneous with an increase of the volcanic activity. According to an account given by T. A. Jaggar,[1] the main volcanic outbreak began on January 12, at 10:05 A.M., after several days in which volcanic earthquakes occurred in swarms. The intensity of the eruption increased during the afternoon. At 6:29 P.M., there was a terrific earthquake, recorded on seismographs in Europe, and simultaneously a sudden lava glow was observed on the smoke from the volcano, continuing for some time. The detonations reached a maximum of intensity at midnight. Jaggar's conclusions are stated as follows:

> It seems probable that the big earthquake of Monday evening was the climax of strain in the crust of the earth's surface, and that the midnight detonations were the climax of the explosions in the lava column that had been released. The glow which occurred at the time of the quake was probably due to the spouting lava.

A connection between volcanism in general and earthquakes is brought out in an investigation made by H. H. Turner for the Seismological Committee of the British Association.[2] Records of volcanic eruptions and of earthquakes for the one hundred and ten years, 1790–1900, were studied with reference to periods of increasing and decreasing activity of the two manifestations, and a factor of correlation of 0.39 ± 0.05 was derived. He says: "The conclusion seems justifiable that earthquakes and eruptions are affected by the same cause." It appears that in a broad way the phenomena are fundamentally related, and it is perhaps not surprising that occasionally the manifestations should be simultaneous.

[1] "Sakurajima, Japan's Greatest Volcanic Eruption," *Nat. Geog. Mag.*, Vol. XLV (1924), p. 441.

[2] *Report of the British Association for the Advancement of Science* (1913), p. 65.

[*To be continued*]

ON THE MECHANICS OF DIKE INTRUSION

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ABSTRACT

This paper considers the mechanics of intrusion of large dikes as exemplified by the Medford Dike in eastern Massachusetts. Associated with the large dike are many older cross-dikes belonging to at least seven systems. A careful mapping of these dikes shows clearly that they have not been offset by the intrusion of the large dike. This suggests that the Medford Dike did not intrude the country rock by pushing aside the walls of a fracture, but rather that the country rock formerly occupying the dike chamber was removed by some process of stoping. Evidence is set forth to show that a theory of piecemeal stoping is not as satisfactory an explanation as a hypothesis of large-block stoping—i.e., that the whole block formerly occupying the dike chamber sank downward in the upwelling basaltic magma.

INTRODUCTION

One of the unsettled problems of igneous geology is that concerning the mechanics of intrusion. Geologists are agreed as to the manner in which laccoliths and sills attain their position, but the problem of batholithic injection is still a subject of controversy. Do the great granitic masses stope their way upward, or does the rising magma force aside the country rock, or is there a combination of both processes? As for dikes, most geologists agree that they intrude the country rock by forcing aside the walls of a fracture. In many cases the evidence is indisputable. Many petrologists, however, have had difficulty in applying this theory to our larger dikes, but for want of other evidence accept the displacement theory.

A careful study of the field relations of one of the larger dikes, the Medford Dike (described below), shows conclusively that the dike was not emplaced by magma entering a fracture and forcing aside the country rock; instead, the evidence is almost irrefutable that this large dike attained its present relations through some sort of stoping, either piecemeal or large scale.

GENERAL RELATIONS OF THE MEDFORD DIKE

The Medford Dike occurs in eight different outcrops in the cities and towns to the west of Boston. It strikes N.12° E., but two of

the outcrops are not on the strike of the rest of the exposures. The distance between the most northerly and the most southerly exposure is ten and a half miles. The width of the dike in the northern area averages four hundred feet, and in the southern field one hundred twenty-five feet. Between these two fields there is a gap without outcrops of five miles. Where observed, the contacts of the dike are nearly vertical. The rock is mainly a coarse diabase, tending toward a gabbro.

DESCRIPTIVE GEOLOGY AT PINE HILL, MEDFORD

A careful study of the field relations of the Medford Dike was made at the most northerly of the outcrops, in the vicinity of Pine Hill, Middlesex Fells. In this area the dike has been eroded out to a depth of approximately fifty feet by glacial scouring. The country rock in the northern portion of the Pine Hill region is a granite (Devonian?) and in the southern part we find rhyolites of Carboniferous (?) age.

One of the most important features is the series of basic dikes intruding the granite and rhyolite. They vary in width from a few inches to forty-six feet; most are regular, but some are irregular; they strike in every direction; some are very dense, some medium textured, and still others are porphyritic.

Various petrographic types are represented among the cross-dikes; the types may be gathered into two major groups: diabases and metadiabases. (1) The diabases are typical augite-labradorite rocks with ophitic texture. A subclass is a variety characterized by pink granular augite and microcline amygdules. (2) The metadiabases are more altered than the diabases and consist essentially of labradorite and a green or brown hornblende. This type of rock is considered to be an altered diabase. A subclass is characterized by partially resorbed plagioclase phenocrysts. (3) In addition to the two major types, there is an actinolite-augite-diorite, represented by dike *N*. It is composed of beautiful idiomorphic brown hornblende with a core of augite or actinolite. (4) Occurring very commonly in the granite in irregular masses is a rock composed essentially of quartz and epidote. These irregular masses are probably partially metamorphosed xenoliths of some sedimentary rock. In at least

two instances, however, these epidosite masses have the structural characteristics of dikes.

By means of the principle of intersection, aided considerably by petrographic considerations, the cross-dikes may be grouped into eight systems, all of different ages. The accompanying table gives the essential data on the systems of cross-dikes.

The cross-dikes are obviously not younger than the Medford Dike, for in only two places, both outside of the Pine Hill area, do

TABLE I

THE SYSTEMS OF CROSS-DIKES

Age	Rock Species	Distinctive Characteristics	Strike	Dikes
IX.....	Diabase	Aphanitic	(N.)	At least two such dikes known; not in Pine Hill area
VIII...	Medford Diabase	Coarse texture	N. 20° E.	Medford dike
VII....	Diabase	Pink granular augite. Microcline amygdales. Tend to strike N.	N. 55° W.	*A, H, M, Q, Z*
VI.....	Diabase	Colorless augite. Great width	N. 85° W.	*D, S, T, X*
V.....	Metadiabase and Diorite	Brown hornblende*	N. 90° W.	*C, O, N*
IV.....	Porphyritic metadiabase	Partially resorbed plagioclase phenocrysts	N. 45° W.	*R*
III.....	Metadiabase	Green hornblende*	N. 75° E.	*AA, I, B*
II.....	Metadiabase	Aphanitic. Green hornblende*	N. 60° W.	*E, K*
I.....	Epidosite	Irregular contacts	N. 15° W.	*J*

* Both green and brown hornblende occur to a greater or less degree in all the metadiabases; but the brown variety is dominant in System V, and the green type in Systems II, III, and IV. Where green and brown occur together, the former is zoned about the latter.

they cut it. Many facts demonstrate to the field worker that the cross-dikes are older than the Medford Dike, and are not offshoots from it:

1) Texture. The Medford Diabase is typically a coarse-grained plutonic rock, even where narrowest. In Brookline it is as coarse as elsewhere, although only a hundred feet wide. North of Pine Hill, where only forty feet in width, it is as coarse as at other localities. Yet the cross-dikes are always relatively dense, even dike *C*, which is forty-six feet wide.

2) Petrographical characteristics. Special petrographic features of the cross-dikes such as the partially resorbed plagioclase phenocrysts in dike *R*, or the microcline amygdules and pink granular augite of dikes *Q* and *X*, are lacking in the Medford Diabase.

3) Dike systems. The very fact that the cross-dikes can be grouped into systems, each system characterized by its own peculiar lithology, strike, and texture is incompatible with the idea of one age for all the dikes.

4) Contact of cross-dikes with Medford Dike. The contact of dike *E* and the main dike is exposed at the western margin of the latter. It is perfectly clear that *E* is cut off. Dike *K* is almost as good an example.

5) Lack of embayments in cross-dikes. Although actual contacts are rare, exposures near the contact of the main dike and cross-dikes are abundant, and show clearly that there are no embayments of coarse diabase into the fine, such as we should expect if the cross-dikes were offshoots of the main dike.

MEDFORD DIKE AT PINE HILL

A careful mapping of the Pine Hill region shows that the Medford Dike is a perfectly straight intrusion, in general three to four hundred feet in width. Just north of the area mapped by the writer the dike tapers down to forty feet in width; farther north, glacial drift covers the exposures. A feature that early impresses the field worker is the great difference in the two contacts of the main dike. The western contact is sharp and straight, with a vertical dip. At the contact the dike rock is a fine diabase with idiomorphic brown hornblende; small amygdules of microcline are arranged in planes parallel to the contact. The rock gradually increases in coarseness toward the center, the normal diabase being reached twenty feet from the western contact. The eastern contact is a sharp contrast to this. In both ground plan and section it is wavy and irregular. The rock is of a hybrid type, at the actual contact almost always a granophyr or a quartz diabase; throughout the seventy-five feet to the west of this contact, lenses and veins of granophyr and quartz diabase are very numerous in the normal diabase. The chilled phase of a hornblende diabase is rarely present at this eastern contact.

It should be emphasized that the contact does not appear to be the result of piecemeal stoping; there are no sharp, angular embayments. It is wavy, with the appearance of having been corroded.

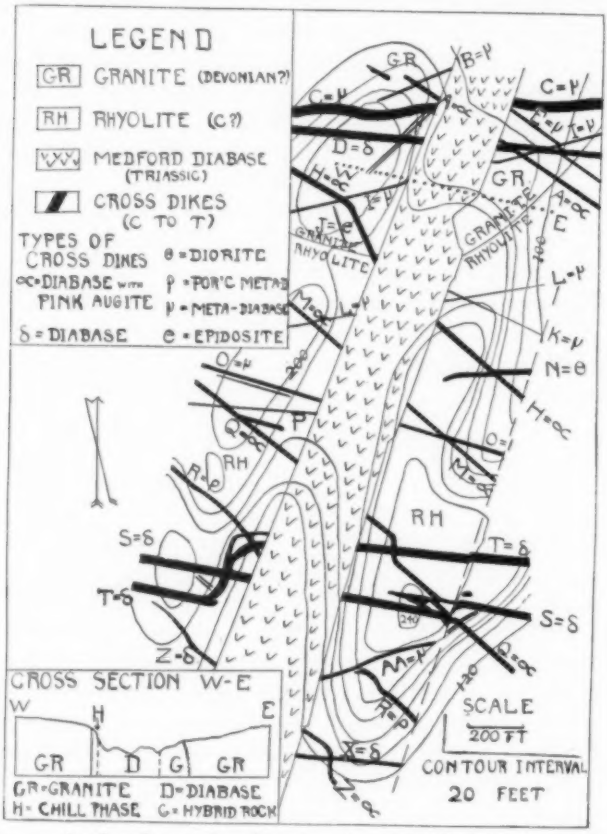

FIG. 1.—Areal geology and geological section of Medford Dike, at Pine Hill, Medford, Massachusetts

From this brief description it will be seen that the Medford Dike may be compared to a sill up on end. The western wall with its dense chilled phase of a brown hornblende diabase represents the floor of the sill. The eastern wall, with its hybrid rock, the quartz

diabase, and the granophyric lenses, represents the upper contact of the sill.[1] The igneous mass is distinctly a dike, however, and not a sill, for it strikes at right angles to the trend of the rocks of eastern Massachusetts.[2]

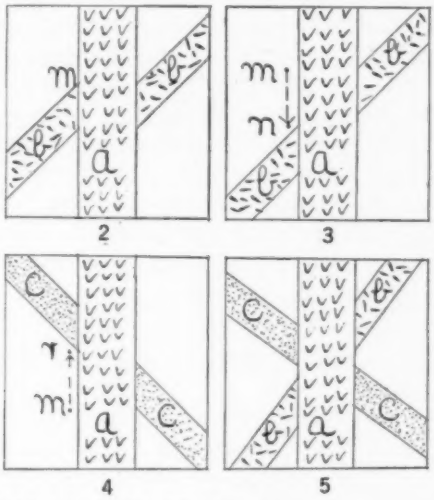

FIG. 2.—Offset in *b* produced by intrusion of *a*.

FIG. 3.—Dike *b* with no offset; apparently produced by horizontal shift from *m* to n.

FIG. 4.—Same as Fig. 3, only with the dike *c* striking northwest, the observed offset suggesting a northerly movement from *m* to *r*

FIG. 5.—Ideal representation of situation at Pine Hill: dikes striking in various directions with no offset. The impossibility of the faulting hypothesis is evident, for a net shift in two opposite directions cannot occur.

MECHANICS OF INTRUSION

It has already been shown on a previous page that the cross-dikes are not offshoots of the Medford Dike, but belong to earlier series of intrusions. If a dike *a* (see Figs. 2–5) cuts an older dike *b*. the older dike should be offset as shown. If the Medford Dike was intruded by a mechanism that forced apart the wall rocks, all the

[1] It should be emphasized that this relationship of the various phases to the two contacts is probably true only in the Pine Hill district.

[2] In the Boston Basin and vicinity the folded rocks strike east and west.

cross-dikes should show offsets similar to that shown in Figure 2. But there are no such offsets in the cross-dikes. Some geologists may maintain that faulting accompanying or following the intrusion would account for the apparent extension on the same strike of the cross-dikes. For example, a horizontal movement (see Fig. 3) might push one part of dike *b* from *m* to *n*, thus accounting for the alignment of the two parts of dike *b*. This is quite possible. But if there is a cross-dike *c* striking in a different direction (see Fig. 4), but also not offset, we must assume a shift to the north. If *b* and *c* occur together (see Fig. 5), neither offset, we cannot invoke horizontal faulting; obviously it is impossible to get a net shift in two opposite directions. An examination of the Pine Hill district (see Fig. 1) shows that the cross-dikes have not been offset by the intrusion of the Medford Dike. Whatever once occupied the space now filled by the Medford Diabase has clearly been replaced, not displaced. Inasmuch as the cross-dikes are striking in many directions, we have conclusive evidence that horizontal shifting does not explain their alignment.

Another fact is of assistance in forcing us to the conclusion that the wall rock has not been pushed aside: the lack of correspondence between certain structures on the opposite side of the main dike. For example, both dikes *K* and *P* are very prominent on one side of the main dike, yet missing on the other. If a single fracture cut the country rock and molten magma forced the walls apart, we should expect to find the same structures on the opposite sides of the main dike. If, on the other hand, the country rock was replaced, it is quite possible that the structures on opposite sides would be different, dikes *K* and *P* having "died out" in the rock formerly occupying the area of the Medford Diabase.

Finally, the granite protrusion on the east wall (see map, Fig. 1) in the northern part of the field has no corresponding embayment in the western wall, such as is necessitated if we believe that the two walls moved apart.

There is no possibility of explaining the facts noted in the three preceding paragraphs by a rotational movement of the blocks on either side of the main dike. If there had been any rotation we should expect consistent differences in the dip of the cross-dikes on

opposite sides of the Medford Dike. None of the dikes betray such a rotation. Three dikes striking in different directions are, very fortunately, exposed in cliff faces on both sides of the main dike. The data given in Table II are conclusive.

As to the possibility of vertical differential movements—the eastern section having gone up or down with reference to the western section—dike *C* gives particularly conclusive evidence. It has a relatively low angle of dip and considerable difference in elevation in the exposures on the opposite sides of the Medford Dike. The dip is 54° N.; the difference in elevation of the west and east sections is seventy feet. Such figures should give an apparent offset of fifty feet, assuming no vertical movements. This is approximately the value of the apparent offset noted. Certainly there has been no

TABLE II

Dike	Strike	Dip (East Section)	Dip (West Section)
A	N. 52° W.	90°	90°
I	N. 95° W.	76° N.	74° N.
O	N. 78° W.	87° N.	85° N.

great vertical movement. Other dipping dikes lead us to the same conclusion.

Neither horizontal nor rotational nor vertical differential movements of the opposite sides of the main dike have taken place. The map conclusively shows that the cross-dikes are continuous on the opposite sides of the main dike; they are not offset. The granite and rhyolite that once occupied the space now filled by the Medford Diabase has not been pushed aside; they are not present in the wall rock; they have been removed.

Piecemeal stoping—A possible mechanism by which this replacement might be effected is piecemeal stoping, of the type advocated by Daly.[1] But there are numerous difficulties in applying such a hypothesis to this case.

1) The shape of the dike. At Medford the dike can be traced continuously for nearly two miles; probably the diabase extends

[1] *Igneous Rocks and Their Origin*, pp. 194–208.

as a dike for at least ten miles, varying in width from one hundred twenty-five to four hundred feet.[1] We can readily conceive how such an irregular, more or less oval-shaped body as a batholith can be formed by piecemeal stoping. But to have the long, narrow, straight magma chamber of the Medford Dike produced by such stoping is wellnigh a mechanical impossibility.

2) The nature of the contacts. It has been noted elsewhere that the western contact, as traced for three hundred feet, is a vertical plane surface. There are no such irregularities as would be expected from piecemeal stoping. The eastern contact, it is true, is irregular. But it is wavy, and there are no sharp re-entrants and apophyses, phenomena which we connect with stoping.

3) The lack of inclusions of country rock. It is a peculiar fact that although quartzite inclusions (a rock foreign to the immediate vicinity) are present, inclusions of the country rock are very rare. This lack of inclusions of the country rock, however, may be accounted for. The quartzite inclusions are often considerably corroded, indicating some assimilation; is it not probable that granite and rhyolite, being bimineralic rocks, would be assimilated more rapidly than the monomineralic rock quartzite?

4) The high basicity of the dike rock. One objection that may be raised to piecemeal stoping and assimilation is the fact that the dike rock shows only a slight salic tendency. If it had stoped off and assimilated all the granite and rhyolite formerly in the dike chamber, it is to be supposed that the dike rock would be monzonitic; certainly not a gabbro. Two points may be noted in this connection. First, may not the supposed syntectic magma have been differentiated at a later stage, the Medford Diabase representing the lower portions of the magma chamber? In the second place, a dike is not necessarily an end in itself; we know that they are frequently conduits for lava flows. Nor does the amount of rock in a dike give any indication of the amount of magma that has passed through. In the case of the Medford Dike, perhaps there was an early granitic or monzonitic magma, but the continual flow of pure basalt from below gradually cleansed the dike of all traces of the early salic magma. Or as a third supposition, the inclusions may

[1] Except for its most northerly outcrop, see. p. 143.

not have been assimilated, but passed out into the surface as solid blocks.

In summation, the last two objections—the lack of granite and rhyolite inclusions, and the high basicity of the dike rock—need not condemn the hypothesis of piecemeal stoping. But the first two—the shape of the intrusion and the essential straightness of the western contact—are fatal objections.

Piecemeal stoping along a fracture zone—The objections to piecemeal stoping might lose their force if we could conceive of the magma eating up into a highly fractured zone of the necessary shape. Such a hypothesis is worthy of consideration, but seems more open to objection than the hypothesis offered below.

Large-block stoping—The material once occupying the dike chamber has certainly been removed. If not by piecemeal stoping, then how? The sharp, clearly defined western contact indicates that a great mass of rock moved at once. The hypothesis that is proposed is that the whole mass of rock formerly occupying the site of the dike moved as a single block, or a few large blocks. This would still be a form of stoping, but instead of the piecemeal type, it is large-block stoping. Such a long, narrow block moving up or down between two fractures is similar mechanically to the grabens of the world—the Great Rift Valley of Africa or the Rhine graben and its offshoots. Such a hypothesis accounts for the dike-like shape of the intrusion and the sharp, straight western contact. As to whether the block actually moved up or down there is no evidence. From a consideration of specific gravity figures of *molten* basalt and *cold* solid granite, it seems quite possible that the great block may have sunk in the upwelling magma.[1]

SUMMARY

Several facts indicate that the Medford Dike intruded the preexisting terrane by means of a mechanism whereby the country rock was replaced rather than pushed aside. The lines of evidence are: (1) the fact that the cross-dikes are not offset, as they should

[1] The hypothesis of large-block stoping here proposed is similar in many respects to Richardson's hypothesis of mechanical stoping. W. A. Richardson, "The Problem of Batholithic Intrusion," *Geol. Mag.*, Vol. LX (March, 1923).

be if the walls of a fracture were pushed apart by rising magma; (2) the fact that a few dikes are found on only one side of the main dike, suggesting that they "died out" in the area now occupied by the Medford Diabase; and (3) the fact that there is no embayment in the west wall of the main dike to correspond to a large protrusion of granite from the eastern wall. It is shown that neither horizontal nor vertical nor rotational faulting has occurred on the opposite sides of the main dike. Two alternate hypotheses are proposed to explain the mechanics of intrusion: (1) piecemeal stoping along a fracture zone; or (2) large-block stoping. The latter hypothesis is favored; it suggests that the whole mass of country rock which formerly occupied the dike chamber moved as a unit, or practically so, the upwelling magma filling the chamber so formed. There is no evidence as to whether the great block moved up or down.

In conclusion, it is suggested that other dikes may be found to have been intruded through a similar mechanism, accompanied occasionally by more or less piecemeal stoping and assimilation. The writer wishes to express here his thanks to Professor J. B. Woodworth, who first observed the phenomenon of the cross-dikes and under whose guidance the present work was carried on; to Professor E. S. Larsen, for valuable petrographic assistance; and to Messrs. Robert Lee, Arthur Wildes, and Howard Gale, Jr., for assistance in the detailed mapping of the area.

DISCOVERY OF LIFE IN THE ARCHEAN

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As was pointed out recently by the writer,[1] the work on the origin of iron-bearing chert formations in northern Minnesota led to the examination of thin sections of the Archean Soudan formation and the overlying Huronian conglomerates.[2] Micro-organisms were found in chert pebbles of the Huronian conglomerate directly overlying the Soudan formation. The Soudan formation itself is recrystallized to such an extent that all traces of organisms seemed to have been destroyed. A thin section has been found now, however, which proves the existence of algae in the Soudan formation. The specimen contain-

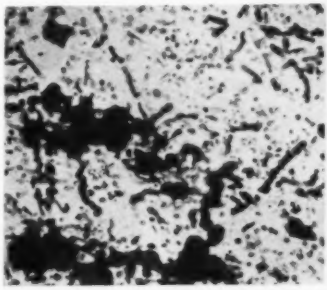

FIG. 1.—Algae (probably blue-green). ×280. Heavy black areas are magnetite crystals.

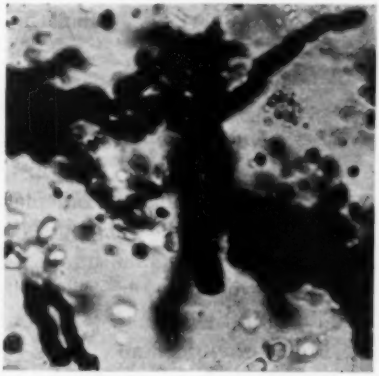

FIG. 2.—Part of same slide as Figure 1. ×910

[1] J. W. Gruner, "Algae, Believed to Be Archean," *Jour. of Geol.*, Vol. XXXI (1923), p. 146.

[2] N. H. Winchell, "Geology of Minnesota," *Geol. Nat. Hist. Surv.*, Vol. IV (1899); J. M. Clements, "The Vermilion Iron-bearing District of Minnesota," *U.S. Geol. Surv.*, Mon. 45 (1903); C. R. Van Hise and C. K. Leith, "The Geology of the Lake Superior Region," *ibid.*, Mon. 52 (1911).

ing the fossils comes from the main belt of the Soudan formation just north of Armstrong Lake in the SW. $\frac{1}{4}$ of Sec. 14, T. 62 N., R. 14 W. The Soudan iron formation lies on the Ely greenstone and is infolded with it. Offshoots of Giants Range granite cut the iron formation in many places.

The specimen is banded black jasper, which consists chiefly of bands of black chert and magnetite. The black color of the chert (now finely crystalline quartz) is due to innumerable microscopic to submicroscopic crystals of magnetite. The magnetite crystallized last. Grains of it are cutting across and replacing parts of the organic structures. Amphibole needles are common in the chert. The organic structures are found through the larger part of the thin section but are especially well developed along a somewhat more cherty band in it. The organisms are black in color, though when highly illuminated and magnified the thinner portions are brown. Figures 1–3 show the wormlike shapes and branching forms, but photographs cannot show the intricate winding of the structures which may be seen under the microscope by focusing up and down in the section.

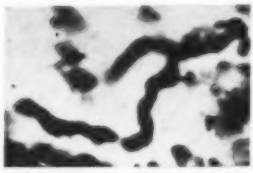

FIG. 3.—Branching form of algae. ×450.

Professor Josephine Tilden, algologist of the University of Minnesota, had the kindness to examine the slide. She finds that the shapes and sizes of the organisms resemble very closely those of certain blue-green algae.

A DISCUSSION OF N. L. BOWEN'S PAPER, "THE PROBLEM OF THE ANORTHOSITES"[1]

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ABSTRACT

In an article by N. L. Bowen on "The Problem of the Anorthosites," he developed his idea on gravitational differentiation of magmas. Like all of Bowen's works, this one is succinct, which, however, does not affect its clearness, but the hypotheses and theses exhibit many misunderstandings. Attention is called to these in this paper.[2]

THE TEMPERATURE QUESTION

First of all, is the temperature question of the anorthosites and all monomineral rocks such a sharp outstanding one in general, as represented by N. L. Bowen? The question of the temperature of monomineral magmas is not a new one for Russian petrographers. In 1911 Loewinson-Lessing[3] called attention to the fact that the melting-point of monomineral magmas is higher than of the bimineral and polymineral ones. From the standpoint of the theory of solutions, the observation of the eminent Russian petrographer does not meet any objections. Before anyone else, he stated a fact to which perhaps no due attention was paid, but he did not attach to it such high importance as Bowen does.

The question, more closely examined, practically leads to the following: Let us provisionally suppose, in spite of all that is known, that rocks are precisely of the same composition as the magmas from which they have been formed. Thus the melting-point of quite pure labradorite magma (i.e., typical anorthosite after Bowen and Vogt) would, according to Bowen, in this case, be equal to $1450° \pm 2°$ (labradorite $Al_1\ An_2$) and anorthite magma to

[1] *Jour. Geol.*, April–May, 1917.

[2] The following paper presents, with some unessential abbreviations, a translation of an article printed in the (Russian) *Geological Journal*, Vol. IV, No. 1–6 (1918–1921), pp. 85–113. The author was then able to make use of geological literature up to 1918.

[3] "Technical and Natural Division," *Proceedings of the Polytechnical Institute of Petrograd*, Vol. XV (1911), pp. 240 and 243.

1550°±2°.[1] Now, with the same supposition, let us take a bimineral magma of olivine and diopside, i.e., the ideal magma of limburgites, pycrites, verlites, and those peridotites which contain a considerable quantity of diopside and are therefore excluded by Bowen from monomineral rocks. The lowest melting-point of such magmas—a eutectic containing 88 per cent diopside and 12 per cent forsterite—is, after Bowen, equal to 1386°–7°,[2] but the temperature rises sharply with the increment of forsterite in the magma, which, of course, corresponds more to the composition of the just-mentioned magmas than to the eutectic. According to Bowen, we have[3]

	Diopside	Forsterite	
For mixture of	80 per cent	+20 per cent	melting-point =1450°
For mixture of	70 per cent	+30 per cent	melting-point =1552°
For mixture of	60 per cent	+40 per cent	melting-point about =1600°

and so on up to pure forsterite, the melting-point of which is 1890°+20°−25°, after Bowen and Andersen.[4]

For preciseness, it is necessary to point out that here forsterite is represented throughout, but not olivine, the temperature of which, according to C. Doelter,[5] is difficult to determine, owing to the decomposition of ferric olivines at melting. Vogt's[6] data give a lower melting temperature for olivine than for forsterite, yet evidently not to the extent to change greatly these values.

The temperature range of an ideal labradorite magma will fall still lower, if, holding in view the clauses just mentioned, we compare its temperature with that of ideal bimineral magmas consisting of olivine and rhombic pyroxene, namely, harzburgites [saxonites] and lherzolites: the invariant point of the forsterite-clinoenstatite

[1] N. L. Bowen, "Melting Phenomena of the Plagioclase Feldspars," *Amer. Jour. Sci.*, Vol. XXXV (1913), p. 582.

[2] N. L. Bowen, "The Ternary System: Diopside-Forsterite-Silica," *ibid.*, Vol. XXXVIII (1914), pp. 210–11.

[3] *Ibid.*, p. 211.

[4] N. L. Bowen and Olaf Andersen, "The Binary System MgO–SiO_2," *ibid.*, Vol. XXXVII (1914), p. 491.

[5] *Handbuch der Mineralchemie*, Vol. II, Part I (1914), p. 307.

[6] I. H. L. Vogt, "Über anchi-monomineralische und anchi-eutektische Eruptivgesteine," *Skr. Videns-Selsk.*, Vol. I, No. 10 (1908), p. 24.

liquid lies at 1557°.[1] These examples might be multiplied, and, resting on our principal supposition, it may be shown that the magma of allivalites[2] should have a higher, and the magma of troctolites almost an equal, temperature to anorthosite magma, etc., etc.

In a word, we should be led to the conclusion that the basic magmas have a higher temperature than the acid, and that, in particular, there is nothing pre-eminent in the anorthosites in this sense save that already pointed out by Loewinson-Lessing.

Evidently, the anorthosites, after corrections have been made for natural conditions, will hold no specific position in view of all that is known about the rocks adduced for comparison. Vogt,[3] at the very foundation of theoretical petrography, deemed it necessary to point out that "it is self-evident that the results obtained [in research on slags] cannot be transferred *sans phrase* to eruptive rocks," and that corrections should be made for the presence of water, carbonic acid, fluorides, chlorides, etc. There is no doubt that these corrections should be applied to all, though perhaps in a different measure, both to acid and basic rocks, to monomineral as well as to polymineral rocks. In this respect, the investigations of the volcanologists are of great significance, for instance, that adduced by F. von Wolff[4] and in particular the newest observations made by A. L. Day and E. S. Shepherd,[5] Frank A. Perret,[6] and F. A. Jaggar, Jr.,[7] on the Hawaiian basalts. All these observers note the presence of water vapors and gases, and give different calculations only as to the quantities of juvenile products: H_2O, SO_2, CO_2, CO,

[1] *Op. cit.*, Vol. XXXVII, pp. 489 and 496.

[2] A. Harker, "The Geology of the Small Isles of Invernes-Shire," *Mem. of the Geol. Surv., Scotland* (1908), pp. 70, 79, 80, and 89; O. Andersen, "The System Anorthite-Forsterite-Silica," *Amer. Jour. Sci.*, Vol. XXXIX (1915), pp. 424–25.

[3] "Silicatschmelzlösungen. I," *Skr. Videns. Selsk.*, Vol. I, No. 8 (1903), p. 23.

[4] "Der Vulkanismus," Vol. I (1914), pp. 72–123.

[5] "Water and Volcanic Activity," *Bull. Geol. Surv. Amer.*, Vol. XXIV (1913), pp. 573–606 and 707.

[6] A whole series of articles in *Amer. Jour. Sci.*, 1913, and among them particularly: "Circulatory System in the Halemaumau," *op. cit.*, Vol. XXXV, pp. 337–49; "Floating Islands of Halemaumau," *ibid.*, pp. 273–82; "Lava Fountains at Kilauea," *ibid.*, pp. 139–48; and "Volcanic Research at Kilauea," *ibid.*, Vol. XXXVI, pp. 484–86.

[7] "Volcanologic Investigations at Kilauea," *ibid.*, Vol. XLIV (1917), pp. 164–67.

H_2, S, N, Cl_2, etc., present. These observations are very important, for the substances pointed out, which possess a low molecular weight, influence greatly the lowering of the melting-points of the magmas containing them (after Raoult's law on the lowering of the hardening-point of solutions by the equi-molecular quantities of the different dissolved substances). So, for instance, 1 per cent of water (H_2O, molecular weight = 18) has the same effect, in this respect, as $\frac{213.3}{18} \approx 12$ per cent of diopside $CaMgSi_2O_6$, with molecular weight 213.3. If, with this in mind, we turn to the analysis of anorthosites, we find the following. An average anorthosite after Daly[1] contains 0.75 per cent of water and 0.05 per cent of phosphoric oxide, indicating the presence of apatite and consequently chlorine and perhaps fluorine. Adirondack anorthosites from Elisabethtown, i.e., just the part of this magma to which Bowen points especially, contain after W. F. Hillebrand[2] 0.21 per cent H_2O (below 110°), and 0.58 per cent H_2O (above 110°), 0.45 per cent CO_2, 0.07 per cent P_2O_5, and traces of sulphur and Li_2O. These values are for the solidified rock, quite evidently containing much less volatile components than the original magma. To this we may add Bowen's own remark that anorthosites with a very low content of bisilicates contain orthoclase to 5 per cent and even more, and in some cases even quartz. All this is adduced to show that Bowen's statement as to the absence of mineralizers in the anorthosite magma is somewhat hypothetical, even bearing in mind only solidified rocks and not primary melted magmas. Are we, however, in our considerations of the quantity of volatile components in the magmas so much concerned with the constitution of these solidified rocks? Rosenbusch,[3] in his answer to Michel-Lévy, pointed out long ago that he could not speak of boron, fluorine, and other components where he could not see them, and that water does not play such a great rôle (as a mineralizer) in other hypotheses of the formation of eruptive rocks than his. Perhaps the most exclusive examples, in this respect, are the pegmatites of Maine described by E. S.

[1] *Igneous Rocks and Their Origin*, p. 28, col. 63, 1914.

[2] *Bull. U.S. Geol. Surv.*, No. 168 (1900), p. 37.

[3] "Über Structur und Classification der Eruptivgesteine," *Tscherm. Mitteil.*, Vol. XII (1891), p. 381.

Bastin.[1] The solidification temperature of these pegmatites, from the microscopical observation of α and β modifications of quartz, fluctuated in the narrow confinement of 560° and 580°[2] which the author's field investigations also proved. Although Bastin was acquainted with many pegmatite quarries[3] which had been worked for feldspars for many years, he found that (1) rare minerals almost never occurred; (2) in fact, rare minerals among pegmatites of Maine are so rare that they often escape attention; (3) there is a general idea that where there are but few rare minerals, this is rather a seeming appearance than reality, yet this does not agree with the author's observations in New England. The pegmatite, consisting of quartz, with the melting-point of about 1700°,[4] and of orthoclase, with the melting temperature of about 1100°,[5] just before solidifying had a temperature of 580°, and its origin was the same as that of the granites of Maine. Hence a decision as to the temperatures of magmas based only on the mineral constitution of the rocks derived from them should be made very cautiously.

After considering all that has been said above, there will hardly be fluctuations as to join or not to join in Bowen's temperature difficulties. All that we can say is that the fewer the constituents in anorthosite magmas, the higher, *ceteris paribus*, their temperature. If it is necessary to dwell on the temperature question in such a detailed manner, however, two causes may be mentioned. Firstly, Bowen affirms that anorthosites "do not give evidence of ever being at a temperature approaching that requisite to melt plagioclase" (p. 210) (as if such a high temperature of the magma was absolutely imperative), and that "for this reason in part . . . . it is believed . . . . that anorthosite masses are simply collected plagioclase crystals" (p. 211). Secondly, while the temperature question by itself is not of primary importance to the petrographer, it gets a particular in-

[1] "Origin of the Pegmatites of Maine," *Jour. Geol.*, Vol. XVIII, No. 4 (1910), pp. 297–321.

[2] F. E. Wright and E. S. Larsen, "Quartz as a Geologic Thermometer," *Amer. Jour. Sci.*, Vol. XXVII (1909), pp. 420–47.

[3] *Bull. U.S. Geol. Surv.*, No. 420, pp. 31, 50, and 75.

[4] See Olaf Andersen, *op. cit.*, Vol. XXXIX (1915), p. 417.

[5] Cf. J. H. L. Vogt's data (*Skr. Videns. Selsk.*, No. 1 [1904], p. 4) with N. L. Bowen's data (*Amer. Jour. Sci.*, Vol. XXXV [1913], p. 582).

terest in connection with the possibility of the greater or lesser correspondence of the constitution of rocks with the magmas which have produced them (in the sense of containing volatile components), and particularly in connection with Daly's[1] hypothesis of the assimilation of great quantities of the adjacent rocks. In connection with the last circumstance it may be not uninteresting to remark that from Jaggar's precision measurements the temperature of the basalt lava of the Hawaiian Islands is not so high as was formerly supposed. Instead of temperatures of 1260°–30° and 1200°–1300°[2] given by former investigations, Jaggar found the temperature of the lava itself to be 750°–850°[3].

CRYSTALLIZATION-GRAVITATION HYPOTHESIS AND ITS COMPLICATIONS

Let us turn next to N. L. Bowen's hypothesis itself, especially well developed in his paper, "The Later Stages of the Evolution of the Igneous Rocks."[4] A detailed analysis of this hypothesis is out of place in this article. I shall give here briefly the objections against such a hypothesis in its simplest form.

First of all, it must be pointed out that the gravitative-crystallization hypothesis that crystals separated from the molten magma, being heavier than the latter, must settle like the crystals in aqueous solutions, is as old as petrography itself. In 1844 Charles Darwin[5] first proposed it, and it was supported afterward by many geologists. Among recent supporters are M. Schweig,[6] who believes in the possible remelting of the subsided crystals; N. L. Bowen, who denies the importance of this refusion; and, in part, R. A. Daly.[7] However, the gravitative-crystallization hypothesis in its broad application has, among others, such adversaries

[1] *Igneous Rocks and Their Origin* (New York, 1914), pp. 1–563.

[2] See F. von Wolff, *op. cit.*, pp. 39–40.

[3] *Amer. Jour. Sci.*, Vol. XLIV (1917), pp. 207–14.

[4] *Jour. Geol.*, Vol. XXIII, No. 8 (1915), pp. 1–91.

[5] *Volcanic Islands* (London, 1844), pp. 117–24.

[6] "Differentiation der Magmen," *Neues Jahrbuch für Mineralogie, etc.*, Beil.-B. 17, XVII (1903), pp. 516–64.

[7] *Op. cit.*, pp. 223, 227, and 375–79. R. A. Daly is rather inclined to assume the gravitative-liquation hypothesis.

as Harker, Iddings, and Pirsson, and also Daly. The latter, as shown in the footnote, attaches far more weight to liquation-gravitative differentiation. That so many first-rate field petrographers oppose the hypothesis is alone enough to cause doubt as to Bowen's broad generalizations.

J. P. Iddings,[1] without denying the possibility of such a differentiation when opportunity serves, gives the following objections against its broad application.

1. The magma of rocks represents a viscous liquid so that without special proofs no analogy can be drawn with water.

2. The agent of viscosity becomes a very significant one in connection with the form and size of the crystals. Tabular and prismatic forms of the latter greatly increase the surface in comparison with the mass, while small size serves greatly to counteract their sinking in the viscous liquid.

3. One may say that supercooling is the general rule in the usually very slow process of cooling of the magma. Thus, it is highly probable that the interval between the separation of different minerals is not very great,[2] and in many cases the rocks show clear evidence of an almost simultaneous crystallization of all mineral components. That is in full accord with the theory of the separation of solid phases from the mixed solutions of physically similar substances, so that they are able to dissolve one another within comparatively narrow limits of temperature. It is evident that with such almost simultaneous crystallization, the separating crystals catch and bind one another, so that the magma shortly becomes overfilled with them and they find themselves either stationary or the respective displacements are insignificant.

4. To these remarks of J. P. Iddings, one must add L. V. Pirsson's reply,[3] that the convection, necessarily arisen in the closed reser-

[1] *Igneous Rocks*, Vol. I (1909), pp. 270–72.

[2] Cf. A. Lagorio, "Über die Natur der Glasbasis, etc.," *Tscherm. Mitteil.*, Vol. VIII (1887), pp. 421–529. "Not slow crystallization but quick solidification under pressure causes the granite-grained structure, whereby slow cooling is certainly not excluded; on the contrary it is necessary for supercooling and supersaturation . . . . ," wrote Lagorio. Cf., also, N. L. Bowen, "The Order of Crystallization in Igneous Rocks," *Jour. Geol.*, Vol. XX (1912), p. 464.

[3] "Petrography and Geology of the Igneous Rocks of the Highwood Mountains Montana," *Bull. U.S. Geol. Surv.*, No. 237 (1905), p. 188.

voirs of magma by virtue of different conditions of temperature in the different parts of the reservoir, could not help confounding all divisions of specific weight, even though the latter took place in spite of the viscosity.

5. Observations made in nature according to Iddings[1] confirm all this, for "bodies of igneous rocks which are exposed for hundreds of feet seldom, if ever, exhibit recognizable differences in composition in upper and lower portions." L. V. Pirsson[2] also points out that "nothing is more common than to observe great vertical thicknesses of igneous rocks exposed by erosion, often for several thousand feet, and find that they are of uniform character throughout from top to bottom." Finally, A. Harker[3] remarks: "The experience of any field geologist goes to show that it[4] is a rare and exceptional incident."

From N. L. Bowen's "Crystallization-Differentiation in Silicate Liquids"[5] we see that the latter was acquainted with all these objections. Moreover, in 1910 he denied entirely the possibility of the formation of granophyres from diabases through differentiation by specific gravity, and gave four convincing proofs[6] on the impossibility of such a differentiation for rocks of Lake Gowganda. He wrote:

> The explanation which would probably first suggest itself is that diabase and granophyre are normal differentiates from a common magma, influenced by gravity. This assumption would neglect evidence of the Foot Lake contact.[7]

He adds afterward that his explanation of the derivation of granophyres (hydrothermal interaction in contact between diabase and clayey schists) "may be rather common occurrence."[8] In 1915 N. L. Bowen wrote that such an opinion as regards the origin of granophyres at the upper boundary of diabases "was arrived at principally because of difficulty of picturing any process of pure differentiation whereby a quartzose rock could be formed from ba-

[1] *Op. cit.*, p. 270. [2] *Op. cit.*, p. 184.

[3] *Jour. Geol.*, Vol. XXIV (1916), p. 554.

[4] I.e., sinking of crystals.

[5] *Amer. Jour. Sci.*, Vol. XXXIX (1915).

[6] *Jour. Geol.*, Vol. XVIII (1910), pp. 670, 672, 669.

[7] *Op. cit.*, p. 670. *Op. cit.*, p. 674.

saltic magma,"[1] though, as seen from the foregoing quotation (p. 670) gravitation differentiation was known to him in 1910. The cause of such a sharp change of opinion was evidently an experiment made in 1915 with quite pure material in a vessel of a capacity of 25 mm. (height) × 15 mm. (diameter).[2] Here were given his observations on the sinking of forsterite and diopside crystals and the floating of tridymite. However, the author was not satisfied with this only. As a counterweight to the objections known to him on the counteracting influences of viscosity and convection, he analyzes the effectiveness of these factors.

In order to carry on reasonings on the subject of viscosity, Stokes's formula is adduced on the falling of spherical bodies in different liquids. R. A. Daly[3] does the same, for a different case, it is true, but to the same principal purpose. Yet Stokes's[4] formula is hardly applicable, in either case, for similar reasons. Firstly, it is deduced for falling spheres; secondly, it was tested for such substances as mercury and oil (O. F. Jones),[5] or steel and oil (R. Ladenburg),[6] i.e., in both cases for substances different in chemical respect as well as in physical, particularly in specific weight; thirdly, R. Ladenburg has shown that the viscosity, at least for oils, rises sharply—about 25 per cent at each degree—along with the falling of the temperature, and, finally, Tamman has found[7] for the case of supercooled liquids and platinum spheres, that the viscosity more than any other property of liquids increases greatly with the falling temperature. One may truly say, nevertheless, that in Bowen's experiments the crystals fell to the bottom. That is quite true. But it took place at 1430°, and, keeping in mind that which has just been mentioned, what changes may take place at far lower temperatures of magma (remember the measurement of the tem-

[1] "Later Stages, etc.," *Jour. Geol.*, Vol. XXIII (1915), p. 49.

[2] *Amer. Jour. Sci.*, Vol. XXXIX (1915), pp. 176, 179.

[3] *Igneous Rocks, etc.*, p. 203.

[4] *Philosophical Magazine* (4), Vol. I (1851), p. 337.

[5] *Ibid.* (5), Vol. XXXVII (1894), p. 451.

[6] *Ann. d. Physik* (4), Vol. XXII (1907), pp. 23, 287, 447.

[7] *Zeitschr. für Physik. Chemie*, Vol. XXVIII (1899), p. 17.

perature of the lava of Hawaii), we do not know. Would it not be simpler, in this case, to say with A. Harker:

> Since it can scarcely be doubted that crystals are almost always denser than the magma from which they form, the general absence of any evidence of their sinking can be explained only by the viscosity of rock-magmas in the temperature range of crystallization. It is necessary to observe, however, that viscosity, if it follows the laws laid down by physicists, cannot inhibit movement, but can only retard it.[1]

R. A. Daly[2] is still simpler in his mode of saying: "In a few days or weeks stones will sink through, and corks will rise through, a mass of pitch, the viscosity of which is more than a million times that of water." Now this is again theoretically quite true. It is as true as that, with the presence of diffusion in solid matters, in a sufficiently long period of time, the zonal growth in plagioclases of Archean granites must one day disappear. The scale may not seem greatly exaggerated if one compares on one side the lapse of time from Archean to the present with the rate of diffusion in plagioclases and, on the other, the duration of solidification of the natural magma with the velocity of subsiding crystals in it, a subsidence extending to tens and hundreds and sometimes to thousands of meters in spite of all counteracting agents. The argument that the long period of time necessary for the manifestation of effects counteracts the viscosity which is very often repeated by the defenders of gravitative-crystallization differentiation is in truth an argument for great numbers, i.e., *argumentum ad Jovem*, if the numbers themselves are not adduced. There is another argument defending viscosity. When reporting this paper to the Petrographic Section of the Russian Geological Committee,[3] observation was made to me that solid bodies often appeared in aggregates when separated (in heaps) by specific gravity. Again, this is quite right. But this separation is produced by atmospheric agents, and not at all by simple subsidence.

N. L. Bowen's[4] and R. A. Daly's[5] arguments against the action of convection as a factor counteracting the sinking of crystals,

[1] *The Natural History of Igneous Rocks* (London, 1909), p. 322.

[2] *Op. cit.*, p. 203.

[3] March 11, 1921.

[4] "Crystallization, etc.," *Amer. Jour. Sci.* (4), XXXIX (1915), pp. 183–84.

[5] *Op. cit.*, p. 224.

pointed out by L. V. Pirsson,[1] are also unconvincing. I must, however, make the reservation that I do not by this understand "pure heat convection," but convection caused, aside from temperature differences, principally by the circulation of gases.

As it appears, gases have great counteracting influence on the subsiding of crystals. That some kind of convection is going on—of course, not purely thermal in this case—in the present craters of volcanoes is proved by F. A. Perret,[2] F. A. Jaggar,[3] and R. A. Daly.[4] Sidney Powers,[5] too, points to the subsiding of fragments of the country rocks in dikes, though in many cases these fragments are lighter than the magma of the dike. That gases must be given off in the displacing or cooling of any form of magma is self-evident from the conception of the word "magma" itself as a mutual solution not only of minerals but also of gases and vapors. At every cooling and displacing upward of the magma, the pressure inevitably decreases, consequently, the gases burst out through the bulk of magma. N. L. Bowen's experiment shows the effect produced. The photograph 1*a*, page 179, in his "Crystallization-Differentiation in Silicate Liquids," gives a clear idea on this subject. Here is represented the section of the lower part of a vessel in which is seen distinctly the gradual enrichment of the glass by forsterite crystals toward the bottom of the vessel. But, in one place, approximately one-fourth distant from the bottom, among the crystals of forsterite three blisters may be seen. Near these blisters the abundance of the forsterite crystals is no less than at the bottom and far greater than in the vicinity. There is no need to add that all this happened in spite of the purity of the substances used in the experiment, and in an almost full absence of gases and vapors (after all there are three blisters), while in natural magmas the incessant rising to the surface of blisters of volatile substances[6] from the bottom of

[1] *Op. cit.*, p. 188.

[2] *Amer. Jour. Sci.*, Vol. XXXV (1913), pp. 273–82 and 337–49.

[3] *Ibid.*, Vol. XLIV (1917), pp. 169–71. [4] *Op. cit.*, p. 259.

[5] "The Origin of the Inclusions in Dikes," *Jour. Geol.*, Vol. XXIII (1915), pp. 180–81. On convection see also the paper of R. B. Sosman, "Types of Prismatic Structure in Igneous Rocks," *ibid.*, Vol. XXIV (1916), pp. 215–34.

[6] Cf. F. A. Perret, "The Ascent of Lava," *Amer. Jour. Sci.*, Vol. XXXVI (1913), pp. 605–8.

the reservoir may change the picture entirely and even reverse it. I wish to remind further that an experiment, in many ways analogous to that of N. L. Bowen's, was made twenty years previous by F. Loewinson-Lessing. He immersed leucite and augite crystals in molten lava. "These researches," wrote the eminent Russian petrographer, "were connected with considerate difficulties," and he pointed out that sometimes crystals heavier than the magma itself would sink.[1]

Such are the rather theoretical objections we should dwell on, though for a short time. For a naturalist the most serious should be deemed the field petrographers' oppositions. "In the experimental philosophy the theorems are deduced from phenomena and are then generalized through induction," wrote the great Newton. For the petrographer such phenomena, i.e., facts, should first of all be field observations. R. A. Daly is well acquainted with this, for he always operates by observations made from facts in nature. Yet he himself could cite[2] out of seventy injections only twenty-nine examples in which the influence of the principle of gravity "is evident," and "six others at least" in which it (control of gravity) is "probable." N. L. Bowen considers this "a host of instances"[3] as a proof of the correctness of his hypothesis, although R. A. Daly declares definitely that "in most [out of thirty-five] cases the available evidence suggests that the units assembled by gravity were liquid fractions, nonconsolute at the moment of differentiation."[4] Among twenty-nine "evident" examples is the Lake Gowganda which was mentioned above, and of which R. A. Daly says in his work,[5] "locally character of differentiation, gravitative," so that A. Harker's remark[6] on this subject that "probably a critical examination would dispose of many of the examples cited" (by R. A. Daly) is not groundless.

All these objections become particularly weighty in connection with the complication being introduced into the gravitative-crystallization hypothesis, in order to explain by its aid the origin of the

[1] "Studien über die Eruptivgesteine," *Compte Rendu* (VII Session Congr. Géol. St. Pétersburg, 1897), p. 347, note.

[2] *Op. cit.*, pp. 229–37.

[3] "The Later Stages, etc.," p. 17.

[4] *Op. cit.*, pp. 229.

[5] *Op. cit.*, p. 230.

[6] *Jour. Geol.*, Vol. XXIV (1916), p. 554.

anorthosites. A priori the self-evident hypothesis, as was pointed out, in this case loses its pre-eminence, because here we have to represent possible separation of plagioclase from diopside during the simultaneous crystallization of both these minerals. The agent of viscosity in this case gets a particular importance, other conditions being equal, in connection with the lower temperature of the crystallization of the eutectic, by virtue of undercooling, the inevitable concomitant of slow crystallization, and also in consequence of the fact that the friction between the sinking crystals, $Ab_1 An_2$, and the liquid of the composition K, must be very great. To be sure, when the crystals sink in this liquid, they must, so to say, dissolve and recrystallize, changing gradually in their composition from $Ab_1 An_2$ to $Ab_1 An_1$. What ought to be the corrections for Stokes's formula, made for the case when the friction coefficient of gliding on the surface of the sphere is equal to infinity,[1] we are not aware, nor do we know that this formula is admissible at all. Let us, however, provisionally assume that it is so. N. L. Bowen observed in his experiments (1) the sinking of forsterite and (2) diopside and (3) the emersion of tridymite crystals from the molten mass.[2] Having made suppositions analogous to those of N. L. Bowen, we shall get results represented in the table on page 166.

The confrontation of the numbers of the two latter columns greatly undermines the hypothesis, even though all positions of departure of the author be assumed to be correct and applied to artificial melts only. And the more so since for N. L. Bowen himself the only difference, namely, that between the specific weights of the solid and liquid phases, is not satisfying. Mind his two sentences: "It is perhaps slightly lighter than the magma, but usually *not sufficiently so* to cause it to accumulate locally,"[3] and also, "In the meantime the liquid eventually becomes *decisively lighter* [difference of the specific weights = 0,115] than the plagioclase crystals."[4]

There is still another objection connected with viscosity. In his article, "The Later Stages of the Evolution of the Igneous

[1] Comp. O. L. Jones, *op. cit.*, p. 451.

[2] "Crystallization-Differentiation in Silicate Liquids," *Amer. Jour. Sci.*, Vol. XXXIX (1915), pp. 176–82.

[3] *Jour. Geol.*, Vol. XXV, p. 212. [4] *Ibid.*, p. 213.

Rocks," in the note on page 15, Bowen pointed out that "magnetite crystals 0.1 mm. in diameter would sink in most granitic magmas no faster than feldspar crystals 0.4 mm. in diameter." Judging from all descriptions of anorthosites, feldspars, in them, possess far greater size than the bisilicates, and, in part for Adirondack anorthosites, W. L. Miller decidedly writes: "In spite of much granulation it

TABLE I

Crystals			Liquid in Which Crystals Sink Down or Emerge		Diff. of Specific Weight for Sol. and Liq.	Temperature
Case	Comp.	Specific Weight	Composition	Specific Weight		
1.....	Mg_2SiO_4	3,216*	Diopside, 56%+ $MgSiO_3$, 44%	2,820†	+0.396	1430°
2.....	$CaMgSi_2O_6$	3,275‡	(Diopside, 56%+ $MgSiO_3$, 44%) 92%+SiO_2, 8%	2,771§	+0.504	1420
3.....	Tridymite	2,270‖	(Diopside, 75%+ $MgSiO_3$, 25%) 85%+SiO_2, 15%	2,729§	−0.459	1430
With anorthosite....	Ab_1An_2	2,710‡	Point *K* of Bowen's diagram: Diopside, 31%+ $Ab_{65}An_{35}$, 69%	2,595§	+0.115	1220¶

* N. L. Bowen and O. Andersen, *Amer. Jour. Sci.*, Vol. XXXVII (1914), p. 498.

† N. L. Bowen, *ibid.*, Vol. XXXIX (1915), p. 187.

‡ F. von Wolff, *op. cit.*, pp. 47–48.

§ The numbers are obtained additively from composition of the liquid phase: specific weight of SiO_2 (glass) 2,213 (F. V. Wolff, *op. cit.*), and for the point *K*—specific weight of plagioclase glass $Ab_{65}An_{35}$—2,489 (*ibid.*).

‖ C. N. Fenner, "The Stability Relations of the Silica Minerals," *Amer. Jour. Sci.*, Vol. XXXVI (1916).

¶ It is necessary to have in mind that it is a temperature obtained by laboratory researches and that the temperature of natural magma is, evidently, far lower.

seems certain that the typical original rock (before thorough consolidation) was characterized by a coarse porphyritic texture,"[1] with great feldspar crystals that "quite typically stand out in a finer grained . . . . ground mass." It is clear, however, that whatever is applicable to magnetite and orthoclase may be applied in a greater degree to diopside and labradorite.

Just so are accentuated all objections for the case of the anortho-

[1] "Origin of the Foliation in the Pre-Cambrian Rocks of Northern New York," *Jour. Geol.*, Vol. XXIV (1916), p. 613.

sites, both relating to possible interference of crystals (Iddings' third reply) settling in this case, not almost at the same time but simultaneously, and, relating to gases, the last portions of which must separate in this ultimate stage of crystallization. Besides, the rocks at the base of the anorthosites were nowhere observed, so that we cannot confirm the statement that the differentiation of the magma which yielded anorthosites arose, indeed, *in situ*. On the contrary, Rosenbusch[1] pointed out, after Matthew, that in a not large gabbro-dome in New Brunswick the composition changed in this manner: at one end of the dome the rock consists of anorthosite and at the other end (but not beneath) of peridotite.

N. L. Bowen writes (p. 215): "It seems possible, that, *locally at least*, plagioclase crystals might accumulate in a mass free from diopside crystals," and then he discusses this local accumulation, I would say, too regionally. But, then, need we say, that the author considers the separation by specific weight of leucocratic parts from melanocratic (precise sometimes to 1 per cent) as complete in nature as is obtained (a hard task!) in the separation of *equally crumbled* minerals in a common laboratory vessel.

For the rest, perhaps all these objections concerning anorthosites, at least in part, are not so significant or necessary. The author himself owns the indisputable difficulties of his explanations, and he says in conclusion:

> It must be admitted, however, that opinion as to whether the process can take place is not a very decisive matter. More important is the deduction of its consequences followed by survey of the characteristics of anorthosites in order to determine to what extent they agree with the requirements.[2]

The author's deductions of consequences are as follows: protoclassic structure, absence of dikes, and absence of effusive equivalents.

PROTOCLASTIC STRUCTURE

If protoclastic structure is, indeed, a characteristic of anorthosites, then it is necessary to show that it exhibits itself where no other explanation of the causes of its formation can be applied, and, secondly, there should be adduced instances where it was observed

[1] *Mikroskp Physiographic*, Vol. II, Part I (1907), p. 360.

[2] *Op. cit.*, p. 217.

only in anorthosites and totally absent in adjoining rocks. Among N. L. Bowen's analyzed instances there is none that would meet these special requirements. In the Morine anorthosite area the author noted "*intense shearing* of the rock which took place partly during this later stage of crystallization and partly immediately subsequent thereto." As regards the Adirondack he writes:

> The Adirondack area is one of the considerable disturbance. It no doubt suffered some disturbance at the time of the intrusion of these igneous masses, and it has unquestionably been much faulted since their consolidation.

Consequently, in both cases we have the right to account for the protoclastic structure on the basis of dynamic action. Moreover, one may cite an instance when the exhibition of such a structure is quite indispensable from the standpoint of N. L. Bowen's theory, and yet it was not observed. R. W. Schaefer[1] adduces an instance of "fairly pure labradorite rocks" occurring as dikes in Lombardy near Ferrero, one being 8 mm. thick, the other "with a very sharp salband" being 15 cm. thick. It would seem, particularly in the latter case, that here are at hand all conditions for the appearance of the protoclastic structure, and yet the author, describing similar appearances in other rocks,[2] did not utter one word about such a structure in the description of a labradorite rock. So must it fare also with the not large dome of anorthosites described by D. W. Matthew.[3] Certainly there are not many localities where anorthosites are found: these two instances make up the small table of outcrops of these rocks given by R. A. Daly.

The matter stands no better for the second requirement. W. J. Miller, an impartial observer in this respect, writes with regard to the anorthosite area of the Adirondacks.

> The great bulk of the rock is *highly feldspathic* and practically *devoid of foliated structure*, probably partly because of lack of minerals favorable for its production or accentuation, while *the more gabbroic* (especially finer-grained) *types are almost invariably well foliated*, frequently excessively so. All of the varieties show more or less *granulation*, sometimes to a high degree, *this being*

[1] "Der basische Gesteinszug von Jvrea in Gebiet des Mastallone-Thales," *Tscherm. Miner. und Petrographische Mitteilungen*, Vol. XVII (1898), pp. 501, 513.

[2] *Op. cit.*, pp. 508, 510, 511, and 515.

[3] "The Intrusive Rocks near St. John, N.B.," *Trans. New York Acad. Sci.*, Vol. XIII (1893–94), pp. 197, 201–12.

particularly true of the less coarse-grained *gabbroic types*. As regards the amount of granulation of the feldspar, it is probably not very different in anorthosite and syenite-granite. The gabbroic, well-foliated, and granulated facies are developed on a grand scale around the borders of the great anorthosite area, but similar types are often encountered irregularly distributed throughout the area.[1]

ABSENCE OF DIKES OF MONOMINERAL ROCKS

The remaining two characteristics of anorthosites and monomineral rocks in general—absence of dikes or effusive equivalents—are not new to Russian petrographers. F. Loewinson-Lessing in a short article, already cited, called attention to this circumstance and, what should be particularly emphasized, came to conclusions just the reverse of those of Bowen. Loewinson-Lessing writes: "The adapting of the monomineral rocks to intrusive formation is another highly valuable indication that the locality of differentiation ought to be looked for in the depth of the earth, in the anteeruptive phase"[2] (*in dem abyssischen Magma*—summary in German, *ibid.*, p. 243), while N. L. Bowen, as we have seen, stands all the time for differentiation *in situ*.

As to the absence of dike facies, this is not quite confirmed by data in petrographic literature. It is true, F. Loewinson-Lessing, in speaking of bostonites, doubts, from absence of data, their monomineral nature, but he does not cite H. W. Turner's albitites, which represent, judging from description and analysis, an almost pure albite rock (porphyric albitite from the region of Tuolumne: SiO_2—67, 53; Al_2O_3—18, 57; Na_2O—11, 50; K_2O—0.10; CaO—0.55; H_2O (higher than 110°)—0.31; H_2O (lower 110°)—0.15; and of the remaining 1.63 per cent; sum total—100, 34 per cent).[3] It must be remarked that the author does not doubt the magmatic nature ("portions of igneous dikes," p. 728) of similar dikes occurring in the same pure state in some places of the Sierra Nevada. As to N. L. Bowen, he considers all albite and oligoclase dike rocks, and also many other monomineral dikes, to have been formed through water solutions, yet without giving any evidences which might well have

[1] *Op. cit.*, pp. 612–13. Italics everywhere mine.

[2] *Proceedings of the Polytechnical Institute of Petrograd* (1911), p. 240.

[3] Further contributions to the "Geology of the Sierra Nevada," *Ann. Rept. U.S. Geol. Surv.*, No. 17, Part I (1895–96), p. 727.

been expected for such a categorical statement.[1] At any rate, the above-mentioned pyroxene anorthosite from Elisabethtown, with 0.59 per cent H_2O (+110°)+0.21 per cent H_2O (−110°) (S=0.80 per cent) might be classed from the point of view of composition, with greater right with such rocks, than the albitite of Tuolumne with 0.31 per cent+0.15 per cent=0.46 per cent H_2O. There is, however, as we have just seen, also almost pure labradorite rock which contains besides grains of plagioclase quite a subordinate amount of amphibole, or sporadically, bronzite-bastite. It forms a dike of 15 cm. thickness with "very sharp selvages."[2] The author, it must be marked, emphasizes the latter circumstance, and describes another labradorite dike, 68 meters in thickness, as "tightly soldered and bound [*verlöthet und verbunden*] with garnet norite" (*op. cit.*, p. 501). It belongs to the category of dikes, which are "tightly soldered with the lateral rock and intruded into the latter to its ultimate solidification" (p. 512), contrasting thus this dike to the dikes with sharp selvages. Such an insertion of labradorite rock into a fissure of 15 cm. hardly differs from injections into lateral not comagmatic rocks.[3] Regarding other monomineral rocks besides peridotites and anorthosites, there might be also mentioned pyroxenites, often fairly pure (see analyses in textbooks), of which H. Rosenbusch says that "they occur pre-eminently or exclusively as dikes in gabbros and peridotites."[4] For the explanation of the absence of dikes in anorthosites it may be reminded that "in beds [Lager] and stocks [of granites], sidebranches penetrating the lateral rock sometimes do not occur,"[5] and there are probably not fewer of such outcrops than all anorthosite outcrops taken together.

[1] It will not be superfluous to note, to the case, that almost pure plagioclase rock from Norway (C. F. Kolderyp, *Bergens Mus. Aarborg*, Vol. VII [1898], pp. 46–47) does not consist of labradorite and even not of andesine-labradorite, as N. L. Bowen claims, but of oligoclase. There is no reference made to its water origin—it is probably connected with banatite of the area.

[2] R. W. Schaefer, *op. cit.*, p. 513.

[3] To the occurrence of dunite (and not peridotite) dikes in the Ural Mountains the geologist, A. N. Zavaritsky, called my attention at the mentioned session of the petrographic section.

[4] *Elemente der Gesteinslehre* (1910), pp. 220–21.

[5] Dr. E. Weinschenk, *Grundzüge der Gesteinskunde*, Part II (1907), p. 43.

ABSENCE OF MONOMINERAL EFFUSIONS

There is quite another matter regarding the effusive equivalents of monomineral rocks. Up to the present they have never been observed. However, this circumstance alone should hardly force us to dwell on N. L. Bowen's hypothesis, which is indisputably hard to comprehend.

Now, firstly, mark here the fact that we know but very few genuine effusive quartz-porphyries belonging to pre-Cambrian or Cambrian and Silurian. An examination of the textbooks of Zizkel[1] or Rosenbusch[2] will show that the quantity of effusive equivalents of granites of the indicated age is quite trifling in comparison with the quantity of granites of the same age. The latter were still deemed by Zizkel, in 1894, to be chiefly old rocks, not later than Dias,[3] in spite of the almost countless outcrops of these rocks known even then. Certainly all the important masses of anorthosite, occurring in but a few places in comparison with granites, belong to pre-Cambrian or at latest to Silurian. R. A. Daly denies that it is possible to explain the absence of effusive facies on the basis of erosion during the many centuries between the Paleozoic and the Present, for "that would imply a perfect denudation not matched in the normal batholitic-volcanic associations of the pre-Cambrian."[4] Accepting, however, the foregoing proportions of granite and quartz porphyry outcrops, and also the few of anorthosite, we shall hardly find R. A. Daly's speculations very convincing and wonder at the absence of effusive equivalents of anorthosites.

F. Loewinson-Lessing in the work cited brings forward two more considerations on this subject: (1) "monomineral magmas as being less fusible and more viscous do not possess satisfying mobility to rise to the surface of the earth in liquid state, or even to rise through small fissures as dike rocks, and (2) these magmas are highly capable of assimilations, consequently on their way to the surface they easily turn into mixed magmas." R. A. Daly also writes that "there is good evidence of high viscosity [of anorthosites] . . . . at the time of intrusion." Yet, by what is this high viscosity caused,

[1] *Lehrbuch der Petrographie*, Vol. II (1894), pp. 182–86.

[2] *Mikrosk. Physiographie*, Vol. II, Part II (1908), pp. 814, 816, and 822.

[3] *Op. cit.*, p. 73. [4] *Op. cit.*, p. 322.

and why does he consider the molten olivine or labradorite more viscous than, for instance, the magma of quartz porphyries, since all data of experimental petrography state just the opposite? These questions are not answered.

Though we have no direct evidences at all that the effusive equivalents of genuine monomineral rocks cannot occur, there is, notwithstanding, a very probable confirmation that they should occur as effusives far less commonly than the effusive magmas of bi- and polymineral ones even though monomineral magmas should occur as widely distributed as the latter. Indeed, we know that aphyric or pure vitreous lavas are far less common than those with intratelluric phenocrysts. This indicates that under the given conditions whereby a rising magma must travel a fairly great distance to the place of its extrusion, the process of cooling is such a rapid one that in most cases one component (sometimes two or three) commences to crystallize. Let us note, now, that a monomineral rock, *ceteris paribus*, has a higher temperature of melting than a bimineral one with one of its components like that of the monomineral. Consequently, the crystallization of monomineral effusives, must, under the same conditions, commence far earlier than bi- and polymineral ones. Besides, in the magmas of the latter two rocks there is a certain interval in crystallization (perhaps it is long enough in the conditions of dike and effusive phases) of one, two, or three components. First, there crystallizes only one mineral and then the eutectic of two, or, for three mineral magmas, first one mineral, then the eutectics of two, and at length the eutectic of three.[1] There is no such interval for monomineral rocks (or, what is truer, the interval is not very large by virtue of rapid separating, for instance, plagioclases of isomorphic layers never attain, under these conditions of rapid cooling, equilibrium with the solutions). Under comparatively rapid crystallization in the fissure or the outlet channel, the crystals are formed at once at many points, the magma rapidly fills with increasing crystals and loses the capacity of easy mobility. This circumstance makes it easy to explain the very rare occurrence of effusive, and the comparative rarity of dike equivalents, of monomineral rocks.

[1] If these three minerals do not form among themselves solid solutions.

AN OPHIACODONT REPTILE FROM THE PERMIAN OF KANSAS

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ABSTRACT

A specimen of ophiacodont reptile (*Winfieldia hilli*, gen. et sp. nov.) is described from the Permian Fort Riley limestone of Kansas. Its morphology, its deposition in a marine formation, and the stratigraphy of Paleozoic vertebrate remains from the Northern Plains are discussed.

INTRODUCTION

The Permian reptile described below was found by Dr. Matt Hill, of Winfield, Kansas, exposed in the Fort Riley limestone in the bed of Walnut River a short distance below that city. Recognizing its importance, he called the attention of Dr. R. B. Dunlevy, of Southwestern College, to the specimen. Subsequently it was obtained in exchange by the late Dr. S. W. Williston. The skeleton was removed in a number of blocks of the matrix; these have since been fitted together and developed by Mr. Paul C. Miller. The present aspect of the specimen (No. 454, Walker Museum) is shown in Figure 1. It is clearly an ophiacodont "pelycosaur," a type known otherwise only from the Wichita of Texas and the New Mexican Permo-Carboniferous. In most of its characters it is very similar to *Ophiacodon*, and frequent references are made below to the description by Williston and Case[1] of the best-known skeleton of this genus.

DESCRIPTION

The fossil was evidently deposited with its ventral surface downward; the sacral region, ventral ribs, interclavicle, left anterior limb, and several fragments of the skull are still in the original position. Subsequently the vertebral column was broken anterior to the sacrum, and the skull, presacral vertebrae, and ribs were

[1] E. C. Case and S. W. Williston, "Permo-Carboniferous Vertebrates from New Mexico," *Carnegie Institution of Washington, Pub. No. 181* (1913), pp. 37–59.

FIG. 1.—Type of Winfieldia hilli. Walker Museum No. 454. About one-tenth natural size.

moved to the left and deposited with the right side turned upward. The clavicles are widely displaced; the right anterior and left posterior limbs have been lost or are buried in the matrix.

The skull is poorly preserved. In outline and size it compares closely with *O. mirus*. A number of characteristic teeth, or their impressions, are preserved *in situ*. The right premaxilla, bearing three teeth, and a tooth-bearing portion of the maxilla are found at the right. The mandible appears to have a straight lower edge, in contrast with the usual curvature in ophiacodonts; this, however, may be due to imperfect preservation.

The cervical vertebrae are poorly preserved; more posteriorly a series of ribs and vertebrae (about the tenth to twenty-first), in much better condition, bend away to the left. These agree as far as is known with the corresponding ones in *O. mirus*. No intercentra are visible. The neural arches are not preserved; but a photograph of the specimen as originally found shows several, which agreed in proportions with *O. mirus*.

A short series of vertebrae including the sacrals and the first six caudals are preserved, but badly weathered. The outlines of the first five right postsacral ribs are, however, perfectly preserved. (This region was damaged in the *Ophiacodon* described by Williston and Case.) They are curved sharply backward, paralleling each other (and in life the ilium), and diminish rapidly in size, the first reaching back nearly as far as the fifth. Typical chevrons are found between the fifth and sixth caudals and posterior to the sixth. This is in contrast with the specimen of *O. mirus* referred to, in which chevrons are absent on six, and possibly seven, anterior caudals.

The ventral-rib system is well developed in the ophiacodonts; Williston and Case, and Williston,[1] have described good specimens. The present skeleton, however, is considerably more complete, and possesses almost the entire series, either the bones themselves or perfect impressions in the matrix (Fig. 2). The ribs are exposed from the dorsal (internal) surface, and run backward from a point slightly anterior to the distal end of the interclavicle to a distance of 360 mm. from the termination of that bone. On the right side the

[1] S. W. Williston, "The Osteology of Some American Permian Vertebrates. II. *Theropleura*," *Contrib. Walker Museum*, Vol. II (1916), pp. 178–89.

ribs are somewhat appressed; on the left they are apparently in natural position, and spread out to a distance of 110 mm. from the mid-line. The more anterior ventral ribs are found slanting out and backward anterior to the end of the interclavicle, and may have met one another beneath that bone, as suggested by Williston.

FIG. 2.—Detail of figure 1, showing ventral-rib system. About three-tenths natural size.

However, the ribs just back of the termination of the bone meet one another at a very acute angle; it is possible that the anterior ones terminated at the edge of the interclavicle. The point cannot be settled by either this specimen or the one described by Williston. A short distance posterior to the clavicle, the acuteness of the angle at which the ribs meet one another is diminished, as indicated by Williston's figure (1916, Fig. 35). The process, however, does not

stop here; the angle is progressively decreased, the more posterior ribs having the central portion in the shape of a smoothly rounded curve.

The length of the ventral surface of the trunk available for occupancy by ventral ribs cannot be accurately determined in this specimen. In the Williston and Case specimen of *O. mirus* the distance from the anterior end of the interclavicle to the anterior end of the pubis is about 440 mm. as the specimen has been restored and mounted. I feel, however, that the shoulder girdle should have been placed somewhat more anteriorly, as was the case in most Texas reptiles; in the specimen as mounted the expanded ribs which carry the strongest members of the levator scapulae-serratus anterior muscles[1] are mostly anterior to the scapula, whereas they are normally located beneath or posterior to it. This more anterior position of the girdle is also indicated by Williston's specimen of *Theroplura*, in which the same measurement is about 510 mm. In the present specimen the length of ventral-rib system plus interclavicle is 523 mm. Even when allowance is made for the somewhat larger size (perhaps 10 per cent) of the present specimen, it is obvious that the ventral-rib system must have occupied practically the entire length of the belly, terminating just anterior to the pubis. Laterally, it must have reached approximately to the ventral ends of the dorsal (true) ribs in the case of the longer anterior ones, but contracting toward the pubis in the "lumbar" region.

The interclavicle is preserved in its natural relations to the ventral ribs. As preserved, it measures 163 mm. in length, and is thus half again as long as the Williston and Case specimen of *O. mirus*, but is not far from the 153 mm. of the Williston specimen of *Theropleura*. The clavicles have been dislocated, but are preserved and measure 143 and 125 mm. in length, a part of the upper end of the right bone having been lost. They are characteristically ophiacodont in the lack of the large ventral expansion usual in the "pelycosaurs." A portion of the left scapula is preserved, close to the head of the humerus. The left posterior (true) coracoid and a portion of the right bone are present.

[1] A. S. Romer, "The Locomotor Apparatus of Certain Primitive and Mammal-like Reptiles," *Bull. Amer. Mus. Nat. Hist.*, Vol. XLVI (1922), p. 526.

The left humerus (Fig. 3) is seen from the dorsal side, the distal dorsal surface being in the plane of the slab. It is clearly ophiacodont, as shown by the sharply out-turned supinator process, but is remarkable for the great development of the entepicondyle. The width of the bone distally is 96 mm., or about 90 per cent of the length (107 mm.) This is in marked contrast to *O. mirus* of Williston and Case with measurements of 68 and 100 mm., and with the ratios of a number of New Mexico and Texas ophiacodonts available to me, which range from 56 per cent to 68 per cent. I have, I believe, seen almost every known ophiacodont humerus, and in no case is there an approach to the proportions of this specimen.

FIG. 3.—Humerus of Winfieldia hilli. One-third natural size.

The left ulna, with the olecranon missing, measures 101 mm., an isolated right radius (the left is only slightly exposed) 78 mm. These exceed slightly Williston and Case's figures of 102 and 75 mm. for the complete bones in *O. mirus*. The left manus is seen from the outer side, the ulnare, the fifth metacarpal, and the phalanges of the fifth toe and a portion of the fourth being visible; the rest of the manus is buried deep in the matrix. The phalanges somewhat exceed those of *O. mirus* in length.

The left posterior limb is not preserved, but a considerable portion of the right is present, although the component parts are considerably disarranged. The femur, partially weathered away, is seen from the posterior (external) side, and measures 125 mm. as compared with 117 in *O. mirus*. Of the lower leg, only the lower end of the fibula is present. The fibulare is much weathered, as are the remaining tarsals, all of which are present, however, except the intermedium (astragalus) and the fifth distal carpal. As may be seen from the photograph, they have preserved their anatomical relations, and present further confirmation of the presence of two centralia in the ophiacodonts. The first two toes are adjacent, but not well preserved. Toes three and four, although separated by a short distance, are complete, except for the proximal phalanx of the fourth, and present almost exactly the same dimensions as *O. mirus*.

CONDITIONS OF DEPOSITION

The typical Texas and New Mexican beds in which Permian vertebrates are found are, as noted by Case,[1] almost entirely, if not exclusively, terrestrial. Mr. Paul C. Miller, who has collected very extensively in these beds, tells me that he has never found any indications of marine deposition in connection with vertebrate fossils. In this case, however, the matrix is a marine limestone, with a number of marine invertebrates preserved, including *Bellerophon*, *Myalina*, *Euomphalus*, *Pinna*, and others. A number of these are visible in Figure 1.

This, however, does not mean that the specimen was a marine reptile. Case[2] has suggested that *Ophiacodon* may have lived along the edge of streams, from which it obtained its food; that *Ophiacodon* may have entered the water at times in search of it, and that this was more particularly true of *Theropleura*. But the tail, as noted by Williston and Case, shows no aquatic specializations, and the limbs are of the generalized, land-dwelling pelycosaur type. The only feature in which the present specimen differs markedly from the typical members of the ophiacodonts is in the distal expansion of the humerus. However, the bone is much "twisted," that is, the proximal and distal expansions are at a considerable angle with one another; whereas water types tend to approximate the planes of the two ends. The specimen is undoubtedly a land form, which has been in all probability carried out to sea after its death. The fact that apparently the entire specimen, even to the easily detached clavicles, was brought intact to its place of burial tends to show that the Winfield region lay not far from the shore.

STRATIGRAPHY

Few discoveries of Paleozoic land vertebrates have been made in Kansas or adjacent regions. In 1897 Williston[3] described a single labyrinthodont tooth from a locality near Louisville, Kansas. This specimen was found in a shale "within 100 feet of the Manhattan

[1] E. C. Case, "The Permo-Carboniferous Red Beds of North America and Their Vertebrate Fauna," *Carnegie Institution of Washington, Pub. No. 207* (1915).

[2] *Ibid.*, pp. 139-40.

[3] S. W. Williston, "A New Labyrinthodont from the Kansas Carboniferous," *Kansas Univ. Quart.*, Vol. VI (1897), pp. 209–10.

Limestone" (=Cottonwood), and would appear to be from some member of the Wabaunsee (Pennsylvanian). Dr. Beede, in a personal communication, states that it is probably from the base of the Emporia. Williston's comparison of the tooth with *Mastodontosaurus*, a member of the exclusively Triassic Stereospondyli, tends to complicate the matter. Later researches, particularly those of Watson, have shown that the stereospondyls are merely the last members of the *Labyrinthodontia*, the Carboniferous members of which (*Embolomeri*) have large and typical labyrinthodont teeth.

Moodie, in 1911,[1] described a well-preserved mandible from the "Coal Measures of Washington County, Kansas" (later named *Eobaphetes*). The specimen is clearly a member of the *Embolomeri*, as recognized by Watson,[2] and as may be seen by the structure of the inner surface. The *Embolomeri* are typically Mississippian and Pennsylvanian, but *Cricotus*, a member of the group, continues into the Texas Red Beds. The stratigraphic position of this find is uncertain. It may be from the same horizon as the Washington County plants described by White; this is perhaps the level of the Cottonwood Limestone.[3]

In 1897 Williston[4] reported the discovery of fragments of *Cricotus* and *Clepsydrops* from a locality in Cowley County, about 20 miles east of Winfield. The horizon has been stated by Beede[5] to be the Neosho member of the Garrison formation. This is considered by many writers to be Permian, and is correlated with the lower part of Wichita of Texas. The fossils, as identified by Williston, are in harmony with this. But it may be noted that the identification of *Cricotus* rests merely upon the presence of vertebrae with complete centra and intercentra. These are characteristic not only

[1] R. L. Moodie, "A New Labyrinthodont from the Kansas Coal Measures," *Proc. U.S. Nat. Mus. 39* (1911), pp. 489–95.

[2] D. M. S. Watson, "A Sketch Classification of the Pre-Jurassic Tetrapod Vertebrates," *Proc. Zoöl. Soc.* (London, 1917), pp. 167–86.

[3] J. W. Beede, *Bull. G.S.A. 33* (1922), p. 678, and letter.

[4] S. W. Williston, "Notice of Some Vertebrate Remains from the Kansas Permian," *Kansas Univ. Quart.*, Vol. VI (1897), pp. 53–56.

[5] J. W. Beede, "The Neva Limestone in Northern Oklahoma, with Remarks upon the Correlation of the Vertebrate Fossil Beds of the State," *Bull. 21, Okla. Geol. Surv.*, 1914.

of *Cricotus* but of all the *Embolomeri*, which are predominately Pennsylvanian. The identification of *Clepsydrops* rests upon a single centrum, hardly a safe criterion, especially since Williston states that it differs somewhat in proportions from that of *C. collettii*, and omits Kansas from his localities for this genus in his classification of 1916.[1] (The specimens are unfortunately not available at present.) It is thus quite possible that the lowest Kansas homologue of the Wichita may be the somewhat higher Wreford limestone, as in the table given by Case,[2] even without recourse to the hypothesis of the earlier appearance of Wichita forms in regions to the North and east of the Texas formations.

The present specimen is from the Fort Riley limestone. This is in harmony with the usual correlation of the Chase, of which the Fort Riley is a member, with the Wichita, or a portion of it. The ophiacodonts from Texas are principally from the Wichita and doubtfully the lower Clear Fork. The New Mexico deposits, in which *Ophiacodon* is found, are considered to be roughly homologous with the Wichita.

The only other vertebrate remains from the Northern Plains region are those reported from localities in the Enid formation in northern Oklahoma, somewhat to the southwest of the last two Kansas locations; the remains have been tabulated by Case.[3] The Kay County localities (Nardin, Taylor, Eddy, McCann's quarry) and Orlando appear to be comparable to the Wichita of Texas. *Embolomeri* (*Cricotus*, *Cricotillus*) otherwise found only in the Wichita or lower formations are present, and the *Captorhinomorpha*, characteristic of the Clear Fork, are not recorded. *Seymouria*, a Clear Fork reptile, is recorded by Case from Orlando; but considering the primitive position of *Seymouria*, it, or related forms, may be confidently expected in the Wichita. Beede considers the Kay County horizon to be the equivalent of the basal Wellington of Kansas. On the other hand, the Pond Creek locality seems to be of Clear

[1] S. W. Williston, "Synopsis of the American Permo-Carboniferous *Tetrapoda*," *Contrib. Walker Museum*, Vol. I (1916), p. 235.

[2] E. C. Case, "The Environment of Vertebrate Life in the Late Palaeozoic of North America," *Carnegie Institution of Washington, Pub. No. 283* (1921).

[3] *Ibid.*, No. 207 (1915).

Fork age. *Cricotus* is not recorded, and *Captorhinomorpha* are present. *Poliosaurus* of the Wichita is stated to be present; but closely related poliosaurids are found in the Clear Fork of Texas.

The stratigraphic evidence furnished by tetrapod vertebrates from the Northern Plains area may be summarized as follows: A portion of the Enid, including the Pond Creek locality, may be correlated with the Clear Fork; the lower part of the Enid (including the Kay County and Orlando localities) and the Fort Riley limestone of the Chase are to be correlated with the Wichita; the Garrison is possibly but not certainly Wichita in age; the Cottonwood limestone is perhaps below the Wichita, and the Emporia probably so. This is, I believe, not inconsistent with the findings from the invertebrates, plants, and stratigraphy.

TAXONOMY

Case and Williston have commented upon the difficulty of distinguishing the three described genera of the *Ophiacodontidae* from one another; as a matter of convenience, *Ophiacodon* has been used by Williston for New Mexican specimens, and *Theropleura* for those from Texas. The present specimen, however, can be clearly distinguished from any ophiacodont skeleton hitherto known by the peculiar humerus; and it is highly probable that a more complete skeleton would show further points of difference. It is also very improbable that this animal existed in the Texas and New Mexico regions at the time of the Wichita "Red Bed" deposition, since none of a large number of ophiacodont humeri from these localities is of the type found in the Winfield specimen. These geographical and morphological differences seem to warrant the generic separation of the specimen from the typical "Red Bed" genera; it may be known as *Winfieldia hilli*, gen. et sp. nov., the specific name being in honor of its discoverer, Dr. Matt Hill, of Winfield, Kansas.

I wish to thank Dr. J. W. Beede, Dr. E. C. Case, Dr. Matt Hill, Dr. R. C. Moore, Mr. F. B. Plummer, and Dr. Stuart Weller for their aid and advice.

THE AGE OF THE TRENT MARL IN NORTH CAROLINA[1]

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ABSTRACT

The article describes the Trent formation of North Carolina, heretofore considered to be Eocene in age, and shows, from a consideration of its contained fauna, that it is lower Miocene and about the same age as the silex bed of the Tampa formation of Florida, thus marking the northernmost limit on the Atlantic Coast of known Lower Miocene sediments.

During the past year a comprehensive study of the early Tertiary deposits of North Carolina was undertaken by the writer. The results of this investigation are now awaiting publication by the United States Geological Survey, under whose direction the work was carried out. In view of a surprising discovery regarding the age of the Trent marl, it seems advisable to present a brief summary of this problem in advance of the publication of the complete report.

HISTORY OF THE PROBLEM

The Trent marl was first recognized and named in 1912.[2] Before that time the deposits comprising it had been referred to the Eocene, which was undifferentiated. In Volume III of the *North Carolina Geological and Economic Survey, Reports*, published in 1912, the Eocene was divided into two formations "on the basis of its fossils and its lithologic characters." The name Trent was proposed for what was considered the older division, and Castle Hayne for the younger. No specific station was given as the type locality for the Trent, further than the statement that "the Trent formation received its name from the Trent River, along which it is exposed from the vicinity of Trenton, Jones County, to near the junction of the Trent and Neuse rivers." The outcrop is not continuous along this part of the Trent River, and subsequent investi-

[1] Published with the permission of the Director of the U. S. Geological Survey.

[2] B. L. Miller, *North Carolina Geological and Economic Survey*, Vol. III (1912), p. 173.

gation has shown that several formations are exposed between the points mentioned.

The Trent formation was believed to underlie the Castle Hayne marl, though the two had never been observed in the same vertical section. Little or no work had been done on the Trent fauna at that time, and the age determination of the formation was based entirely on the identification, by Dr. M. W. Twitchell, of four echinoids which he believed "to indicate the Upper Claibornian age of the strata."[1] They are: *Scutella alta* Conrad, *Echinocyamus parvus* Emmons, *Cidaris carolinensis* Emmons, and *Cidaris Mitchelli* Emmons. The exact station from which these forms were collected is not known. Emmons gave the very indefinite locality of "Craven County, N.C." Three of these species have not been recognized elsewhere, and are therefore of little value for determining the age of the horizon. The fourth, *Echinocyamus parvus* Emmons, has been found in Onslow County associated with typical Castle Hayne fossils. The evidence, therefore, on which the Trent was referred to the Claiborne has little significance.

In the 1912 *Report of the State Survey*, twenty-three field stations, referred to the Trent formation, are described in detail.[2] Although fossils were observed at most of these localities, they were not specifically identified. During the recent field investigation, the writer visited most of the Trent localities and collected fossils which subsequently have been determined. Of the twenty-three stations listed as Trent, seven failed to yield fossils and seven proved to belong to the Castle Hayne formation. This discovery has materially altered the recognized areal distribution of the Castle Hayne and Trent formations, but this phase of the problem will not be discussed here.

In 1919 G. D. Harris[3] described two *Pectens* from the Trent formation. One of these was new, and to this he gave the name *Pecten trentensis*. This was the first fossil to be described from the Trent, and Harris remarks that it "is so different from anything we have heretofore found in the Eocene of this part of the United States, owing to a lack of well-known species from the same

[1] *Op. cit.*, p. 177. [2] *Op. cit.*, pp. 179–85.

[3] *Bull. Amer. Paleon.*, Vol. VIII (Ithaca, 1919), pp. 15–16.

locality, its horizon must at present be considered as doubtful." The other *Pecten* Harris referred with a question mark to the Conradian species *elixatus*, which he considered synonymous with *P. poulsoni* Morton, a Vicksburgian species. Sensing the significance of this identification, Harris says:

> . . . . It would seem that a considerably greater geologic range should be given to this species [i.e., *P. poulsoni* Morton] than has been admitted heretofore, else the horizon on the Trent whence these specimens came is far higher than has been suspected.

These observations assume much interest in view of the discovery, set forth in this paper, that the Trent is of Lower Miocene age.

THE TRENT FAUNA

Although centrally located on the Eastern Coastal Plain of the United States, the Trent fauna has, until the present, received no attention whatever from the systematic paleontologist. At its outcrop the Trent formation is principally a hard, impure limestone (commonly called "buhrstone"), which is made up almost entirely of casts of marine shells. The identification of such material is practically impossible unless good fossils of the same age and from the same locality are available for comparison. The discovery of a bed of well-preserved Trent fossils near Silverdale in Onslow County has now made possible a critical study of the fauna. As yet only a small collection has been made from this locality, but it is sufficient to show the presence of a large and varied molluscan assemblage.

A total of twenty-six species of Mollusca have been studied. Fifteen species and one variety are new, belonging to the genera *Turritella*, *Busycon*, *Lyria*, *Scaphella*, *Conus*, *Arca*, *Glycymeris*, *Astarte*, *Crassatellites*, *Venericardia*, *Phacoides*, *Venus*, *Antigona*, and *Macrocallista*. Three species are undeterminable, and the following seven are referred to previously described species:

Calyptraea trochiformis Lamarck
Sinum imperforatum Dall
Oliva posti Dall
Pecten elixatus Conrad (?)
Pecten trentensis Harris
Plicatula densata Conrad
Venericardia (*Cyclocardia*) *granulata* Say

Of these seven species, two came originally from the Trent formation and have not been recognized elsewhere. It is therefore apparent that the Trent fauna is essentially new.

The closest affinities of the Trent species range from the Vicksburg Oligocene to the Upper Miocene. The true position of the Trent is therefore somewhere between these extremes. About 25 per cent of the fauna has its closest affinity with species of the Upper Miocene, 45 per cent with forms in the Lower Miocene, and 30 per cent with Oligocene species. Although the predominance of relationship to Lower Miocene forms is not overwhelming, the fact that the percentage of affinities in the Upper Miocene and Oligocene is nearly equal indicates rather conclusively that the Trent fauna is of Lower Miocene age.

Another fact which strongly confirms this determination is the presence of true *Venus* in the fauna. This genus, as limited by Lamarck, originated and reached its maximum development during the Miocene. Two species of *Venus* occur in the Trent and are among the most prolific forms. They find their closest affinity in *V. halidona* Dall from the Tampa formation of the Lower Miocene of Florida.

The standard Lower Miocene section of the Atlantic Coastal Plain comprises four horizons, which, beginning with the lowest, are the Tampa, Chipola, Oak Grove, and Shoal River formations of Florida. The fauna of the Tampa formation was monographed by Dr. William Healey Dall in 1915.[1] It is correlated with the Lower Aquitanian of Europe, which at that time he considered Oligocene. The Aquitanian, however, is now regarded as Lower Miocene. The three faunas of the higher formations have been monographed by Dr. Julia Gardner, and are now awaiting publication. They are regarded as separated from the Tampa by a conspicuous interval, but are relatively close to one another in point of time. North of Florida the only Lower Miocene horizon that has been recognized on the east coast is the Marks Head marl of Georgia. When the fauna was first studied by Dr. T. Wayland Vaughan,[2] this horizon

[1] "A Monograph of the Molluscan Fauna of the Orthaulax Pugnax Zone of the Oligocene of Tampa, Florida," *U.S. Nat. Museum, Bull. 90*, 1915.

[2] *Science*, N.S., Vol. XXXI, No. 804 (May 27, 1910), pp. 833–34.

was correlated approximately with the Calvert formation of Maryland. It is now, however, considered to be of the same age as the Chipola formation of Florida.[1]

Three of the Trent species have been specifically identified with forms occurring in the "silex beds" of the Tampa formation of Florida, four others have their closest affinity in the Tampa, and one is closely allied to a species occurring both in the Tampa and the Chipola. There is only one Trent species, *Venericardia nodifera* Kellum (MS), which has its nearest relative confined to the Chipola, and in this case the Tampa form *V. serricosta* Heilprin is almost as close as the Chipola affinity. *Pecten elixatus* Conrad is related to *P. poulsoni*, a Vicksburg species, and to *P. burnsii*, a Chipola species. One Trent species, *Scaphella stromboidella* Kellum (MS), has its closest affinity in the Shoal River, and none are nearly related to Oak Grove species. It is obvious, therefore, that of the 45 per cent which have their closest described species in the Lower Miocene, the large majority are related to Tampa forms. The conclusion is therefore reached that the Trent formation is approximately of the same age as the "silex beds" of the Tampa formation of Florida.

[1] Julia Gardner, oral communication.

REVIEWS

Les Hommes Fossiles. By MARCELLIN BOULE. Deuxième édition. Paris: Masson et Cie., 1923. Pp. xi+505, figs. 248. Frs. 40.

Fossil Men. By MARCELLIN BOULE. Translated from the French, with an Introduction by JESSIE ELLIOT RITCHIE and JAMES RITCHIE. Edinburgh: Oliver & Boyd, 1923. Pp. xxvii+504, figs. 250. 36*s.*

Human Origins. By GEORGE GRANT MACCURDY. New York: Appleton & Co., 1924. 2 vols. Pp. xxxv+440, xvi+516, figs. 410. $10.

The Evolution of Man. By G. ELLIOT SMITH. New York: American Branch, Oxford University Press, 1924. Pp. 159, figs. 10. $2.85.

The second edition of Boule's masterly work preserves for the most part the original text, with additions called for by recent discoveries, and with a few changes in the author's conclusions. Descriptions of the Broken Hill, Wadjah, and La Quina skulls are added. His opinion that Pithecanthropus is a giant gibbon is unchanged; the work, however, was in press before recent studies of the interior of the skull were made. He is still inclined toward the negative on the question of the Norfolk eoliths, but is not so firm in his denial of the association of the Piltdown jaw and skull.

The translation of this work by the Ritcheis' is textually excellent, while the make-up is superior to that of the French original. While the translation was made from the first edition, later changes and additions have been included in the text or in a short Appendix.

In *Human Origins* we have the first attempt—and a very successful one—by an American author to cover, in a comprehensive way, the story of prehistoric man and his handiwork. The first of the two volumes treats, in the main, of the Paleolithic period, with chapters on the Ice Age, eoliths, and the Lower and Upper Paleolithic periods, followed by accounts of prehistoric art and fossil men of the period.

In Volume II the transitional cultures, the Neolithic, and the Bronze and Iron ages of Western Europe are considered, with an interesting chap-

ter on the Stone Age culture complex. In addition, a comprehensive and very useful list of prehistoric sites and their contents and a repertory of prehistoric art are given. The illustrations, many from original photographs, number over four hundred.

The main emphasis of the book is upon the culture of prehistoric man, rather than the human remains themselves, which are discussed in two chapters (one of extreme brevity), which seem almost to be appendices to the rest of the two volumes.

To the problem of human evolution, Dr. Elliot Smith comes with the combined points of view of the anatomist, the neurologist, and the anthropologist. The result is a series of novel and stimulating ideas, many of which are set forth in the present book. As the author states in the Preface, the work lays no claim to a complete presentation of his views, but the three lectures, with a Foreword, which the volume contains, give the main outlines of his point of view; he hopes to publish a fuller statement at some future time. The ancestry of man and the principal human fossils are discussed, and the topic of the relationship of early human cultures, upon which his views are at variance with those of many anthropologists, is considered. Especial attention is given to the development of the brain and vision in relation to the evolution of man.

A. S. R.

La Géologie sismologique: Les Tremblements de Terre. By COMTE DE MONTESSUS DE BALLORE. Paris: Librairie Armand Colin, 1924. Pp. 488, pls. 16, figs. 118.

Since this is a posthumous publication, the Preface is by M. Pierre Termier, and there is a bibliographic notice by M. Armand Renier.

La Géologie sismologique, the last work of this celebrated authority on seismology before his death on January 29, 1923, is a great contribution to our science. The author's papers on seismology number approximately one hundred and fifty, and among these are the following exceptional works: *Les Tremblements de Terre: Géographie sismologique* (1906), *La Science sismologique* (1907), *La Sismologie moderne* (1911), *Bibliographie general de Tremblores y Terremotos* (1919), and *La Géologie sismologique* (1923). This vast amount of work has made Comte de Montessus de Ballore particularly qualified to discuss with authority the problems of this branch of our science. This last work of the master-seismologist is a storehouse of observed facts and recorded observations, though perhaps the eager student might wish that more attention had been given to theoretical considerations.

In his Introduction the author puts forward two fundamental laws: (1) the folded structure of the geosyncline is unstable, and inversely the tabular structure of the continental areas is stable; and (2) the earthquake disturbances are a mitigated survival of orogenic and epeirogenic efforts to which are due the relief of the earth. There are, of course, exceptions to these rules, but there are still many new factors to be studied which may account for apparent discrepancies and which may help to clarify the relations between seismic and geologic phenomena.

Seismic disturbances are classified as glyptogenetic or geologic and ectogenetic or external dynamic, the latter including the superficial types such as those due to volcanoes and landslides, while the former may be more or less deep seated and include epeirogenetic and orogenic movements. A large portion of the treatise consists of a discussion of a great many important earthquakes, classified according to the foregoing scheme. There is also an exposition on the seismic effects of landslides and the secondary glyptogenetic effects of earthquakes including a discussion of the isostatic readjustment of alluvial plains and the depression of the coast and continental shelf.

The influence of the terrain and structural irregularities on the isoseismals, particularly faults and differences in induration of rocks, is discussed at length. The intensity of earthquake shock is usually less over areas of high altitude than over contiguous areas of lower altitude; consequently, the isoseismals roughly parallel the contours.

The author indicates that the migration of epicentra is an important problem, one whose solution may lead to earthquake prediction. Although no rules are known as yet to apply to earthquake prediction, the disturbances do follow certain zones and are more frequent there, but the time intervals are variable. There is apparently no regular cycle in earthquake occurrence, or at least no simple one.

Comte de Montessus de Ballore has found that there are three great unstable belts on the earth: (1) the occidental branch of the circum-Pacific geosyncline from Kamtchatka to Melanesia, (2) the Alpine-Himalayan or Mediterranean branch from Gibralter to Burma and Turkestan, and (3) the oriental branch of the circum-Pacific geosyncline from Alaska to Chile. He suggests that it is by the study of the seismic centers at the surface of the earth that we may discover the rôle of earthquakes in the evolution of the relief of the globe throughout the geologic past.

L. F. A.

The Face of the Earth. By EDUARD SUESS. Volume V, Index and Maps. Translated by HERTHA C. SOLLAS. Oxford: Clarendon Press, 1924; 5 colored maps. $5.00. New York: Oxford University Press, American Branch. Pp. xvi+170.

The Face of the Earth has long been famous the world over as a remarkable storehouse of assembled geologic information, but at the same time few books have been more difficult to use satisfactorily, partly on account of the peculiar style of the author and partly because there was no index. The different volumes have appeared slowly from time to time, each one taking a large part of the globe as its field. The method of treatment thus involves rapid jumping from one portion of the globe to another in each volume, which makes the bringing together of the scattered data on any particular region laborious without an index. The much-desired index has finally appeared. It is to be regretted, however, that the index has been delayed until now, when, following the later advances in the fundamentals of geology, the usefulness of the work is on the wane.

Map I is helpful in portraying Suess' analysis of the earth's surface; Map II, his analysis of Europe; and Map III, the recumbent sheets of the Alps. A concise text description adds much to the value of each.

R. T. C.

Boletin del Instituto Geologico de Espana. Terceira Serie, T. V, 1924. Madrid: S. A. Blass.

A thick volume containing many important papers, some on general topics, as the age of the earth according to radioactive determinations, but most of them regional studies of the geology of Spain.

R. T. C.

The Geology of Papua. By EVAN R. STANLEY. Melbourne: Albert J. Mullett, Government Printer, 1924. Pp. 56, figs. 50, 1 colored map.

The known geology of Papua, or British New Guinea, is as yet very fragmentary, for the territory contains much totally unexplored land, and the unraveling of its geology is accompanied by very great difficulties.

With the exception of small littoral strips, the area is extremely mountainous. The sedimentary rocks apparently include strata of pre-Cambrian, Devonian, Jurassic, Cretaceous, Eocene, Miocene, Pliocene, Pleistocene, and Recent age. Most of the effusive igneous rocks are late Tertiary or Recent. Hypabyssal and plutonic rocks of unknown age also occur.

The territory contains commercial deposits of gold, copper, and sulphur, and small amounts of iron and coal. Excellent indications of petroleum are also reported.

L. F. A.

The Geology and Mines of the Waihi District, Hauraki Goldfield, New Zealand. By P. G. MORGAN. New Zealand Dept. of Mines, Geol. Surv. Branch, Bull. 26 (N.S.), 1924. Pp. 218, figs. 9, pls. 7, colored maps 3, plans 5, secs. 4.

This bulletin is the report of a resurvey of the Waihi district, a portion of the Hauraki goldfield in the eastern part of North Island, New Zealand. This region is an example of gold-silver mineralization in Middle Tertiary volcanic rocks consisting of propylitized andesite or dacitic flows, interstratified with minor layers of breccia, tuff, and mudstone. The author finds that the dacitic intrusion postulated by Bell and Fraser does not exist.

The chief lodes occupy fault fissures or zones and consist in the main of quartz, valencianite, and calcite. Pyrite, sphalerite, galena, and chalcopyrite form 3 or 4 per cent of the total. Argentite and enargite also occur. The gold and silver is present as electrum, and is generally extremely fine and associated with quartz and valencianite in such a way that it is contemporaneous and therefore primary.

The ores were deposited from highly heated ascending solutions of magmatic origin. Contrary to previous interpretation, replacement was more important than cavity-filling. The hypothesis of a multiple period of ore-formation suggested by Bell and Fraser is rejected as unnecessary. The region having previously stood at a higher level, oxidation has taken place more than 1,000 feet below sea-level. As a result there has probably been local impoverishment of the deposits and a corresponding enrichment in the deeper portions not yet exploited.

The gold and silver produced in Waihi from 1911 to 1922 was worth approximately £6,333,679.

L. F. A.

Rivers and Lakes. By M. A. C. HINTON. Northumberland Ave., London: Sheldon Press. New York and Toronto: Macmillan Co., 1924. Pp. 182, figs. 17.

This is a simple and concise story of the development of rivers and lakes intended primarily for the beginner in geology.

L. F. A.